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Sports physical therapy spans a wide spectrum, from injury and post-operative rehabilitation to performance enhancement and injury prevention. To truly help people get the most out of their bodies, we need to focus on all three. But many of us don't, and if you're one of them, I think you may be really missing the boat.

There may be two main paradigms holding us back:
1. We spend the majority of time focusing on “function” and not “performance.”
2. The vast majority of the physical therapy profession is focused on injury rehabilitation. This includes both entry level curricula and most workplace settings, which limits our potential to help people maximize their function and performance.

Perhaps this is just semantics or terminology, but I know when I was in school and early in my career, “function” was indicative of people's activities of daily living, and “performance” was related to the realm of sports. Would you agree? That was my early perception, at least. Now, I couldn't disagree with these definitions more.

Here is how I would define them now:
• Function is an activity. Sure, this could include things like bathing and getting dressed, but I would also say running, jumping, throwing, and just playing a sport, in general, is also a function.
• Performance is how well you perform that function.

Performance is not something that only athletes do. We all need to perform at whatever function we want with our bodies. This is probably the most important concept to understand during the rehabilitation process and one that I have continued to promote.

The Need for a Shift Towards Performance Physical Therapy
Here's what I suspect is the typical vision of the performance spectrum to most physical therapists. At any point in time, you have your baseline. Most people then focus on either restoring or enhancing performance based on that baseline.

Figure 1. Current model.

Often, therapists sit back and wait for someone to get injured, then help them restore themselves back to baseline. What if their baseline was part of the reason why they got injured in the first place? What if sports physical therapists were to focus more on prevention?

If we just focus on restoring their function back to their baseline, we're completely missing the boat on helping them optimize and enhance their performance. I can't help but think that this is one of the reasons why so many people have recurring injuries, chronic pain, and failed surgeries. Restoring people back to their baseline isn't enough, we need to build their capacity and enhance their baseline.

As we all know, many things can predispose a person to injury, including weakness, mobility concerns, and imbalances. There has been a recent uptick in criticism on social media that too many physical therapy interventions are either ineffective, transient in nature, or both. Rightfully so. But maybe it's not the physical therapy treatments that are the concern, but rather the overall strategy? Maybe we are focusing too much on just restoring
function, and not enough on optimizing and enhancing performance?

The Goal of Performance Physical Therapy
The goal of performance physical therapy is to raise the capacity of the body, not just restore an individual to baseline function. It’s not enough to simply try to restore someone to their previous baseline. That’s “traditional” physical therapy as compared to sports physical therapy. The sports physical therapist not only restores function, but also works on optimizing and enhancing performance. That’s the key difference to me. If you add optimizing performance to the spectrum, it could look like this:

Figure 2. Performance spectrum.

But I still don’t think that’s enough, we, as sports physical therapists can do better. If you are working on restoring or enhancing performance, you should also be working on optimizing performance.

Realistically, there is an overlap between these concepts.

Figure 3. Performance spectrum continuum.

This changes our focus in a couple of ways:
1. It shows that these concepts all overlap. We can restore and optimize performance, and we can optimize and enhance their performance. Thinking of them as independent factors is not ideal.
2. It shifts our thought process from retrospective to prospective. When you know the endpoint isn’t just to simply restore their baseline, but also to

optimize and hopefully even enhance their performance, it changes your entire outlook on the injury rehabilitation process from day 1.

Our Profession Needs Performance as a Part of Sports Physical Therapy
I have good news for you. Physical therapists are really good at diagnosis and treating injuries. All of the assessment and diagnostic skills that allow physical therapists to evaluate and treat an injury can easily be adapted to also assess someone’s function and level of performance. Think about it, what’s the difference between an evaluation of someone with an injury and someone that is healthy that wants to enhance their performance? Special tests. That’s kinda it, right?

Special tests were designed to help diagnose a specific injury. If this special test, or cluster of tests, is positive, then you may have this injury. But everything else other than special tests essentially evaluate someone’s level of function, right? Strength, mobility, balance, movement. These are all things that we can evaluate to help develop a complete performance therapy and training program for a person. We can then work on optimizing and enhancing each of those qualities.

How do you blend all this together? Treat the injury and optimize the body. All it takes is a shift in your perspective.

Mike Reinold
Systematic Review/Meta-Analysis

Proximal Hamstring Tendinopathy: A Systematic Review of Interventions

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Keywords: buttock pain, hamstring tendon, surgery, tendinopathy

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Background
Proximal hamstring tendinopathy affects athletic and non-athletic populations and is associated with longstanding buttock pain. The condition is common in track and field, long distance running and field-based sports. Management options need to be evaluated to direct appropriate clinical management.

Purpose/Hypothesis
To evaluate surgical and non-surgical interventions used in managing proximal hamstring tendinopathy.

Study design
Systematic review

Methods
Electronic databases were searched to January 2019. Studies (all designs) investigating interventions for people with proximal hamstring tendinopathy were eligible. Outcomes included symptoms, physical function, quality of life and adverse events. Studies were screened for risk of bias. Reporting quality was assessed using the Cochrane Risk of Bias Tool (Randomized Controlled Trials [RCT]) and the Joanna Briggs Institute Checklist (Case Series). Effect sizes (Standard mean difference or Standard paired difference) of 0.2, 0.5 and 0.8 were considered as small, medium and large respectively. Overall quality of evidence was rated according to GRADE guidelines.

Results
Twelve studies (2 RCTs and 10 case series) were included (n=424; males 229). RCTs examined the following interventions: platelet-rich plasma injection (n=1), autologous whole-blood injection (n=1), shockwave therapy (n=1) and multi-modal intervention (n=1). Case series included evaluation of the following interventions: platelet-rich plasma injection (n=5), surgery (n=4), corticosteroid injection (n=2), multi-modal intervention + platelet-rich plasma injection (n=1). Very low-level evidence found shockwave therapy was more effective than a multi-modal intervention, by a large effect on improving symptoms (-3.22 SMD; 95% CI -4.28, -2.16) and physical function (-2.42 SMD; 95% CI -3.33, -1.50) in the long-term. There was very low-level evidence of no difference between autologous whole-blood injection and platelet-rich plasma injection on physical function (0.17 SMD; 95% CI -0.86, 1.21) to (0.24 SMD; 95% CI -0.76, 1.24) and quality of life (-0.04 SMD; 95%CI -1.05, 0.97) in the medium-term. There was very low-quality evidence that surgery resulted in a large reduction in symptoms (-1.89 SPD; 95% CI -2.36, -1.41) to (-6.02 SPD; 95% CI -8.10, -3.94) and physical function (-4.08 SPD; 95%CI -5.53, -2.60) in the short-term.

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INTRODUCTION

Proximal hamstring tendinopathy presents as persistent buttock pain that occurs with activities such as running, sitting and lunging.\(^1,2\) The condition primarily affects active men and women\(^3\) in sports such as track and field, distance running, soccer and rugby.\(^1\) It also afflicts people who do not participate in sport.\(^4,5\) The condition is challenging to manage because of the persistence of symptoms and lack of response to treatment.\(^5,6\)

Interventions for proximal hamstring tendinopathy focus on reducing symptoms and restoring physical function. Common non-surgical interventions include exercise, corticosteroid injection, platelet-rich-plasma injection and shockwave therapy.\(^6,7\) Common surgical procedures include tenotomy, bursal and tendon debridement and removal of adhesions around the sciatic nerve.\(^2,8\)

With many treatment options available, a rational starting point is to systematically review the literature and synthesize information where possible. The purpose of this systematic review was to evaluate both surgical and non-surgical interventions used in managing proximal hamstring tendinopathy.

METHODS

The systematic review protocol (Figure 1) was developed in accordance with the PRISMA statement and preregistered on PROSPERO (ID: CRD42017072678).\(^9\)

A systematic literature search was conducted from the earliest date available until January 2019 for relevant studies published in MEDLINE, CINAHL, EMBASE, SPORTSDISCUS and PUBMED. A comprehensive search was undertaken, with assistance of a librarian, using a combination of keywords and medical subject headings (MeSH). The search strategy was formed around two topics; "hamstring" and "tendinopathy". Synonyms within each concept were combined with OR Boolean operator; and terms between concepts were combined with AND Boolean operator (Appendix 1).

After removal of duplicates, two reviewers (AN and JA) independently scanned titles and abstracts of all papers. Any disagreement was referred to a third reviewer (AS) for consensus. Full text versions of articles were obtained for all remaining studies. To ensure all relevant articles were included, citation tracking (PubMed/ Google Scholar) and reference checking of included studies was performed.

Study designs included were randomized controlled trials (RCTs), prospective (comparative) cohort studies, case-control studies and case series with 10 or more participants.

Articles were confined to English language only. Biomechanical reports and narrative reviews were excluded. Participants of any age diagnosed with proximal hamstring tendinopathy by a health professional were included. Synonyms considered included: hamstring tendinitis, high-hamstring tendinopathy, and hamstring origin tendinopathy. Traumatic injuries such acute proximal hamstring tendon tears, complete hamstring tears or avulsion injuries were excluded.

Surgical and non-surgical interventions were considered in this review. Interventions included, but were not limited to: surgery, shockwave therapy, platelet-rich plasma injections, autologous whole blood injections, corticosteroid injection and multi-modal intervention (NSAIDs, manual therapy, exercise and stretching).

Outcome measures that reported on symptoms, physical function (e.g. return to sport), quality of life (QOL) and ratings of success were included. Short (< 12 weeks), medium (> 12 weeks - 1 year) and long (> 1 year) time-points were considered. Adverse events were reported as a secondary outcome, and were dichotomised as minor or major.\(^10\) Minor adverse events were defined as incidents which had minimal serious or potentially serious effects, such as thigh paraesthesia or a small infection that resolved with antimicrobial drugs. Major adverse events were incidents that had the potential for severe effects, such as deep vein thrombosis or severe infection.

One amendment was made from the initial protocol. Originally only case series were included. This was amended to exclude case series with <10 participants. This was identified as an oversight in the initial protocol and was revised prior to conducting the search. This amendment resulted in the exclusion of three case series with small sample sizes.\(^11–13\)

Pre-specified data was extracted from each study and included eligibility criteria, study design, participant demographics, intervention, outcome parameters, results at all time points and adverse events. Data was extracted by one reviewer (AN) and checked by a second reviewer (AS). Authors were contacted in the case of missing data. If author(s) did not respond, they were contacted again after two weeks. If the author(s) still did not respond raw data was reported.

Means and standard deviations of continuous outcomes for comparative studies (e.g. intervention A vs Intervention B) were converted to standardized mean differences (SMD) with 95%CI using RevMan (version 5.5). When studies reported changes over time, means and standard deviations (SD) were converted to standardized paired differences (SPD) using the ‘metafor’ package (version 2.1–0) within the ‘R’ statistical software package (version 3.5.1). SPD calcu-
lations (with 95% CI) require information about pre- and post-test reliability.\textsuperscript{14,15} If this was not reported, or could not be located, a conservative estimate was used ($r=0.50$). In cases where the SD was not reported, we used the formula provided in the Cochrane Handbook (section 16.1.3.2), using a conservative correlation coefficient of 0.5, to calculate the SD.\textsuperscript{16} Effect sizes (SMDs and SPDs) of 0.2, 0.5 and 0.8 were considered as small, medium and large respectively.\textsuperscript{17} When data could not be presented as a SPD, raw data were presented. The proportion of people who returned to pre-injury level of sport was summarized as a percent with 95% confidence interval (CI). Statistical heterogeneity across pooled studies was assessed using the Tau ($\tau^2$) and $I^2$ statistic. An $I^2$ value of 25%, 50% or 75% was considered a low, moderate or high level of heterogeneity respectively.\textsuperscript{18} The ‘meta’ package, version 4.9-2, of the R statistical software package (version 3.3.1) was used for all statistical analyses (http://www.r-project.org/).

Study quality was assessed using two separate risk of bias tools, depending on study design.\textsuperscript{16} The Cochrane Risk of Bias Tool was used to assess RCTs.\textsuperscript{16} Each of the eight domains were marked as either low risk of bias (+), high risk of bias (-) or unclear risk of bias (?).\textsuperscript{16} Studies with the presence of three or more (-) or (?) were considered as having a high risk of bias. The Joanna Briggs Institute Checklist was used to assess the risk of bias in other study designs.\textsuperscript{19} Items were scored "yes (Y)", "no (N)", "unclear (U)" or "not applicable (N/A)" on the ten point checklist.\textsuperscript{19} If an individual study scored ≥ 6 "yes (Y)" scores, it was considered low risk of bias.

Completeness of reporting in intervention and control groups was assessed using relevant items of the Template for Intervention Description and Replication Checklist (TIDieR).\textsuperscript{20} Improved reporting provides an opportunity to understand the treatments used and more precisely inform clinicians about the type of interventions, enabling replication of treatments in clinical practice. If items were not relevant for an included study, they were scored not applicable (N/A). For example, completeness of reporting of a control group was scored N/A in studies where there was no control/comparison.

Both single group and comparative studies were assessed according to the GRADE guidelines.\textsuperscript{21} Overall quality was defined as high, moderate, low or very low.\textsuperscript{21} A staged process was followed whereby RCTs were first rated as high and case series were rated as low-quality evidence.\textsuperscript{22} Following this step, quality of evidence for individual outcomes were further reviewed, with the potential of being further downgraded by one level for each of the following factors: i) limitations in design ($\geq$25% of the participants from studies with a high risk of bias as determined by the risk of bias tool), ii) inconsistency of results (significant

Figure 1: PRISMA flow chart illustrating study selection process

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statistical heterogeneity ($I^2 > 40\%$) or inconsistent findings across studies ($< 75\%$ of the participants report findings in the same direction), iii) indirectness (i.e. generalization of the findings), iv) imprecision (total number of participants $< 300$ for each outcome and wide confidence intervals) and v) other considerations (e.g. publication bias, flawed design, massive dropout). Single studies ($n = 300$) were considered inconsistent and imprecise, providing "low quality evidence", which could be further downgraded to very low-quality evidence if additional items were not satisfied.

RESULTS

The PRISMA flow diagram, is shown in Figure 1. 1924 studies were identified through database searching. Full texts of 34 studies were assessed for inclusion. Twelve studies met inclusion criteria.

Participant characteristics, study design and diagnostic criteria are displayed in Table 1. A total of 424 (229 males, 195 females) participants were included. Mean ages in individual studies ranged from 24 to 51 years. One-hundred and ninety-nine (47%) participants were described as professional, competitive or high-level athletes, 75 (18\%) were recreational athletes and five participants were non-athletes. Activity levels in 145 (34\%) participants were not reported.

The majority of studies used clinical assessment and imaging to diagnose proximal hamstring tendinopathy (Table 1). The clinical assessments varied between studies. Imaging (magnetic resonance imaging or ultrasound) was used to attempt to verify proximal hamstring pathology in 92\% of studies. A variety of patient reported physical function measures and pain measures were used. Mean follow-up times varied from one week to six years.

The most common intervention was platelet-rich plasma injection. Other interventions included surgery, corticosteroid injection, autologous whole blood injection, shockwave therapy and multi-modal intervention (NSAIDs, manual therapy, exercise and stretching).

Name and description (item 1) and mode of delivery [item 6 (a) and (b)] were reported completely in both intervention and control groups (Figure 5). Intervention adherence (TIDieR items 11 and 12) was not reported in any study. No studies provided adequate details of post-surgical rehabilitation protocols. Risk of bias for RCTs and case series are reported in Figure 2 and Figure 3 respectively.

EVIDENCE FROM RANDOMIZED CONTROLLED TRIALS

There was very low-level evidence from a single RCT that shockwave therapy was more effective than a multi-modal intervention (one week of rest plus NSAIDs, two weeks of manual therapy and therapeutic ultrasound, and three weeks of exercise - including strength training and stretching) by a large effect in the short (-1.84 SMD; 95\% CI -2.59, -1.09), medium (-3.23 SMD; 95\% CI -4.28, -2.19) and long-term (-3.22 SMD; 95\% CI -4.28, -2.16) on self-reported symptoms (Table 2). There was also very low-level evidence that shockwave therapy was more effective than the multi-modal intervention by a large effect in the short-term (-3.09 SMD; 95\% CI -4.04, -2.15), medium (-2.90 SMD; 95\% CI -3.88, -1.92) and long-term (-2.42 SMD; 95\% CI -3.33, -1.50) on physical function. Sixteen athletes (80\%) returned to pre-injury level of sport, at a mean time of nine weeks (range; 6-15 weeks) post shockwave therapy intervention (Figure 4). No participants in the multi-modal intervention group returned to sport at one year.

There was very-low level evidence from a single RCT of no significant difference between platelet-rich plasma and autologous whole blood injection on physical function (0.03 SMD; 95\% CI -0.96, 1.03) to (0.28 SMD 95\% CI -0.76, 1.24) and medium-term (-0.04 SMD; 95\% CI -1.05, 0.97). One complication occurred after platelet-rich plasma injection (irritation of the sciatic nerve).
<table>
<thead>
<tr>
<th>Study (Year)</th>
<th>n (F), mean age (years)</th>
<th>Diagnostic criteria</th>
<th>Tendon involved (%)</th>
<th>Activity level</th>
<th>Average duration of symptoms (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RCTs</strong></td>
<td></td>
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<tr>
<td>Caccio (2011)</td>
<td>40 (13F), SWT 24 years, multi-modal intervention 24 years</td>
<td>At least 2 of the following painful; Puranen Orava test, fast hamstring-stretch test, hamstring strength test MRI</td>
<td>NR</td>
<td>Multi-modal professional athletes: 40</td>
<td>Multi-modal intervention: 21 months (13-81) SWT: 19.6 months (11-72)</td>
</tr>
<tr>
<td>Davenport (2015)</td>
<td>15 (13F), AWB: 45.4 years, PRP 47 years, 17 cases (2 bilateral)</td>
<td>Clinical diagnosis(^a) Positive MRI or US</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td><strong>Case series</strong></td>
<td></td>
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</tr>
<tr>
<td>Benazzo (2013)</td>
<td>17 (5F), 27 years</td>
<td>Reporting pain at ischial tuberosity Pain with concentric hamstring contraction: (positive 47%) Tenderness ischial tuberosity (41% positive) Puranen Orava test (88% positive) Leg raising test (23% positive) MRI</td>
<td>Bicep femoris (41%) Semimembranosus (29%) Semitendinosus (6%) Common tendon (22%)(^a)</td>
<td>Professional athletes: 9 Competitive athletes: 8</td>
<td>23 months (3-48)</td>
</tr>
<tr>
<td>Fader (2014)</td>
<td>18 (12F), 43 years</td>
<td>Clinical diagnosis(^a) MRI</td>
<td>NR</td>
<td>NR</td>
<td>32.6 months (6-120)</td>
</tr>
<tr>
<td>Krauss (2016)</td>
<td>14 (13F), 47 years</td>
<td>At least 2 of the following: Tenderness to palpation at ischial tuberosity, positive bent knee stretch test, positive supine plank test MRI</td>
<td>NR</td>
<td>NR</td>
<td>4.1 years (5 months to 10 years)</td>
</tr>
<tr>
<td>Lempainen (2009)</td>
<td>90 (32F), 34 years, 103 cases(^b) (13 bilateral)</td>
<td>Patient interview and history Pain at ischial tuberosity with hamstring stretch MRI</td>
<td>All semimembranosus</td>
<td>Professional: 5 Competitive: 47 Recreational: 38</td>
<td>NR</td>
</tr>
<tr>
<td>Levy (2019)</td>
<td>29 (22F), 45 years</td>
<td>Clinical diagnosis(^a) confirmed with positive MRI</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Nicholson (2014)</td>
<td>18 (10F), 51 years, 22 cases (4 bilateral)</td>
<td>Pain with prolonged sitting Pain with hamstring contraction MRI</td>
<td>NR</td>
<td>Athletes: 18</td>
<td>28 months (2-120)</td>
</tr>
<tr>
<td>Puranen (1988)</td>
<td>59 (14F), Athletes: 25 years, joggers: 39 years, non-athletes: 35 years, 65 cases (6 bilateral)</td>
<td>Pain on active stretching Pain on palpation</td>
<td>NR</td>
<td>Athletes: 50 Joggers: 4 Non-athletes: 5</td>
<td>NR</td>
</tr>
<tr>
<td>Wetzel (2012)</td>
<td>15 (8F), 38 years, 17 cases (2 bilateral)</td>
<td>Clinical diagnosis(^a) MRI</td>
<td>NR</td>
<td>PRP group: Collegiate or high-level athletes: 9 NR: 1 Multi-modal intervention group: High level athletes: 2 NR: 3</td>
<td>Multi-modal intervention: 7.8 months PRP: 9.6 months</td>
</tr>
<tr>
<td>Young (2008)</td>
<td>44 (16F), 29 years, 47 cases (3 bilateral)</td>
<td>Pain on palpation of proximal hamstring region Weakness at 30º of resisted knee flexion MRI/US</td>
<td>NR</td>
<td>Professional: 4 Semi-Professional: 7</td>
<td>8 cases: &lt; 6 months 15 cases: 6-12 months 10 cases: 12-18 months</td>
</tr>
<tr>
<td>Study (Year)</td>
<td>n (F), mean age (years)</td>
<td>Diagnostic criteria</td>
<td>Tendon involved (%)</td>
<td>Activity level</td>
<td>Average duration of symptoms (range)</td>
</tr>
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<tr>
<td>Zissen (2010)</td>
<td>65 (37F), 37.7 years</td>
<td>Clinical diagnosis&lt;sup&gt;a&lt;/sup&gt; MRI/US</td>
<td>NR</td>
<td>Recreational: 33</td>
<td>14 cases: &gt;18 months</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NR</td>
<td>8 cases: &lt;6 months</td>
<td>15 cases: 6 months to 1 year</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 cases: &gt;1 year</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> AWB = autologous whole blood injection, F = female, MRI = magnetic resonance imaging, NR = not reported, PRP = platelet-rich plasma injection, SWT = shockwave therapy, US = ultrasound
Three studies, recording the results of platelet-rich-plasma injection alone, documented change in self-reported symptoms over time (Table 2). Outcomes could not be pooled due to heterogeneity in measures and incomplete data reporting. There was very low-level evidence that PRP is associated with a large reduction in symptoms over the short-term (-0.92 SPD; 95% CI -1.54, -0.29). A second study found very low-level evidence that platelet-rich plasma injection was associated with a small, clinically significant, reduction in self-reported symptoms (Table 2). Two studies reported changes in physical function following platelet-rich plasma injection(s) over time (Table 2). There was very low-level evidence of a small (-0.44 SPD; 95% CI -0.82, -0.06) to large (-0.90 SPD; 95% CI -1.52, -0.28) improvement in physical function in the short-term (Table 2). Ten per cent of participants returned to their pre-injury level of sport after platelet-rich plasma injection at eight weeks (Figure 4). Two (4%) minor adverse events occurred (short-term high levels of pain post-injection).
<table>
<thead>
<tr>
<th>Study (Year)</th>
<th>Intervention</th>
<th>Mean follow up (range)</th>
<th>Symptoms Effect size (CI) unless otherwise stated (&quot;-ve indicates reduction in pain&quot;)</th>
<th>Physical function Mean effect size (CI) unless otherwise stated</th>
<th>Adverse effects (number %): minor, major</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RCTs</strong></td>
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</tbody>
</table>
| Cacchio (2011) | Multi-modal intervention: NSAIDs, manual therapy, exercise and ultrasound SWT: 2500 impulses at 0.18 mJmm²/ frequency = 10 shocks in 4 separate sessions at weekly intervals. | 1 week, 6 months, 12 months | Patient reported pain rating: VAS:  
   - Week 1: -1.84 (-2.59, -1.09) SMD⁴  
   - 6 months: -3.23 (-4.28, -2.19) SMD⁴  
   - 12 months: -3.22 (-4.28, -2.16) SMD⁴ 
   - ve favours SWT | Patient reported physical function: NPRS:  
   - 1 week: 3.09 (-4.04, -2.15) SMD  
   - 6 months: -2.90 (-3.88, -1.92) SMD  
   - 12 months: -2.42 (-3.33, -1.50) SMD  
   - ve favours SWT | Minor:  
   • SWT: 0 (0%)  
   • Multi-modal intervention: 0 (0%)  
   Major:  
   • SWT: 0 (0%)  
   • Multi-modal intervention: 0 (0%) |
| Davenport (2015) | PRP vs AWB: Single U/S guided injection of AWB (5mL) or PRP (3mL). | 12 weeks, 6 months | NR | Patient reported physical function:  
   - HOS (ADL):  
     - 6 weeks: -0.56 (-1.58, 0.45) SMD  
     - 12 weeks: 0.03 (-0.96, 1.03) SMD  
     - 6 months: NR  
     - ve favours PRP  
   - HOS (SPORT):  
     - 6 weeks: -0.21 (-1.24, 0.83) SMD  
     - 12 weeks: 0.28 (-0.76, 1.32) SMD  
     - 6 months: 0.17 (-0.86, 1.21) SMD  
     - ve favours PRP  
   - MHHS:  
     - 6 weeks: -0.28 (-1.28, 0.72) SMD  
     - 12 weeks: 0.05 (-0.95, 1.04) SMD  
     - 6 months: 0.24 (-0.76, 1.24) SMD  
     - ve favours PRP  
   - Health related QOL:  
     - i-HOT 33:  
       - 6 weeks: -0.80 (-1.86, 0.26) SMD  
       - 12 weeks: 0.01 (-1.00, 1.03) SMD  
       - 6 months: -0.04 (-1.05, 0.97) SMD  
       - ve favours PRP | Minor:  
   • PRP: 1 (10%)  
   • AWB: 0 (0%)  
   Major:  
   • PRP: 0 (0%)  
   • AWB: 0 (0%) |
| **Case series** |              |                        |                                                                                   |                                                                  |                                         |
| Benazzo (2013) | Surgery: Prone incision from ischial tuberosity to 8-15cm distally. Partial transverse tenotomy performed plus sciatic nerve release. | 71.3 months (24-138) | Patient reported pain rating: VAS:  
   - -6.02 (-8.10, -3.94) SPD³  
   • ve favours PRP | Patient reported physical function: Tegner score:  
   - -4.08 (-5.53, -2.63) SPD³  
   Return to sport (pre-injury level):  
     - Proportion:  
       - 6 weeks: -0.80 (-1.86, 0.26) SMD  
       - 12 weeks: 0.01 (-1.00, 1.03) SMD  
       - 6 months: -0.04 (-1.05, 0.97) SMD  
       - ve favours PRP | Minor:  
   • 1 (6%)  
   Major:  
   • 1 (6%) |
<table>
<thead>
<tr>
<th>Study (Year)</th>
<th>Intervention</th>
<th>Mean follow up (range)</th>
<th>Symptoms Effect size (CI) unless otherwise stated (-ve indicates reduction in pain)</th>
<th>Physical function Mean effect size (CI) unless otherwise stated</th>
<th>Adverse effects (number %): minor, major</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fader (2014)</td>
<td>PRP</td>
<td>46 months</td>
<td>Patient reported pain rating:&lt;br&gt;VAS (mean pain):&lt;br&gt;• -2.9 MD&lt;sup&gt;a&lt;/sup&gt;&lt;br&gt;Patient reported rating of symptom improvement:&lt;br&gt;• 10 (55.6%) patients had an 80% or greater improvement at 6 months</td>
<td>NR</td>
<td>Minor: 1 (6%)  Major: 0 (0%)</td>
</tr>
<tr>
<td>Krauss (2016)</td>
<td>PRP</td>
<td>12 weeks</td>
<td>Patient reported pain rating:&lt;br&gt;VAS (mean pain):&lt;br&gt;• -0.92 (-1.54, -0.29) SPD&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Patient reported physical function:&lt;br&gt;LEFS: &lt;br&gt;-0.90 (-1.52, -0.28) SPD&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NR 4 (29%) had worse physical function at 12 weeks (LEFS)</td>
</tr>
<tr>
<td>Lempainen (2009)</td>
<td>Surgery</td>
<td>49 months (range, 12-156 months)</td>
<td>NR</td>
<td>Return to sport (pre-injury level):&lt;br&gt;Proportion: 80/90 (89%) mean 5 months</td>
<td>Minor: 3 (3%)  Major: 4 (11%)</td>
</tr>
<tr>
<td>Levy (2019)</td>
<td>PRP</td>
<td>8 weeks</td>
<td>NR</td>
<td>Patient reported physical function:&lt;br&gt;VISA H: -0.44 SPD (-0.82, -0.06)</td>
<td>Return to Sport (pre-injury level):&lt;br&gt;Proportion: 3/29 (10%) at 8 weeks</td>
</tr>
<tr>
<td>Nicholson (2014)</td>
<td>CSI</td>
<td>21 months (VAS) 24.8 months (LEFS)</td>
<td>Patient reported pain rating:&lt;br&gt;VAS:&lt;br&gt;• -3.28 MD&lt;sup&gt;a&lt;/sup&gt;&lt;br&gt; Improvement in symptoms short term (proportion):&lt;br&gt;• Yes: 14 (78%)&lt;br&gt;• No: 4 (22%)</td>
<td>Patient reported physical function:&lt;br&gt;LEFS/80:&lt;br&gt;• 60 (48.72)&lt;br&gt;Level of function (% of full normal activity):&lt;br&gt;Increased from 28.76% to 68.82%</td>
<td>Minor: 0 (0%)  Major: 0 (0%)</td>
</tr>
<tr>
<td>Puranen (1988)</td>
<td>Surgery</td>
<td>24 months (24-96)</td>
<td>NR</td>
<td>Return to Sport:&lt;br&gt;Proportion: 52/59 (88%)&lt;sup&gt;f&lt;/sup&gt;</td>
<td>Minor: 4 (6%)  Major: 0 (0%)</td>
</tr>
<tr>
<td>Wetzel (2012)</td>
<td>Multi-modal intervention (physical therapy + NSAIDs) vs failed multi-modal intervention + single volume PRP</td>
<td>Multit-modal intervention: 2 months</td>
<td>Patient reported pain rating</td>
<td>Patient reported physical function</td>
<td>Minor: 0 (0%)</td>
</tr>
<tr>
<td>Study (Year)</td>
<td>Intervention</td>
<td>Mean follow up (range)</td>
<td>Symptoms Effect size (CI) unless otherwise stated (-ve indicates reduction in pain)</td>
<td>Physical function Mean effect size (CI) unless otherwise stated</td>
<td>Adverse effects (number %): minor, major</td>
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<tr>
<td>Young (2008)</td>
<td>Injection (6cc) plus additional multi-modal intervention</td>
<td>Failed multi-modal intervention (PRP + multi-modal intervention): 4.5 months</td>
<td>VAS: • Multi-modal intervention: -6.2 MD(^a) • Failed multi-modal intervention (PRP + multi-modal intervention): -7.5 MD(^a)</td>
<td>NPRS: • Multi-modal intervention: -2.2 MD(^c) • Failed multi-modal intervention (PRP + multi-modal intervention): -4 MD(^c)</td>
<td>Major: • 0 (0%)</td>
</tr>
<tr>
<td>Zissen (2010)</td>
<td>Surgery Semi-prone, incision in gluteal fold to gluteus maximus dissection continued toward ischial tuberosity. Sciatic nerve freed and prominent bursal tissue removed.</td>
<td>53 months (range, 9-110)</td>
<td>Patient reported pain rating: VAS: • -1.89 (-2.36, -1.41) SPD(^a)</td>
<td>Patient reported physical function: Weakness score (/10): • -3.69 (-2.76, -4.62) MD(^c) -ve indicates reduction in weakness Return to sport (pre-injury level): Proportion: • Multi-modal intervention: 2/11 (18%) • Failed multi-modal intervention PRP + multi-modal intervention: 9/9 (100%)</td>
<td>Minor: • 11 (23%) Major: • 0 (0%)</td>
</tr>
<tr>
<td>Zissen (2010)</td>
<td>Single CSI to area of maximum pain under U/S guidance.</td>
<td>48 months (6-96)</td>
<td>Patient reported rating: Number (% of patient’s symptoms resolved: • Complete: 11 (29%), moderate: 8 (21%), mild: 10 (26%), no: 9 (24%)</td>
<td>NR</td>
<td>Minor: • 0 (0%) Major: • 0 (0%)</td>
</tr>
</tbody>
</table>


\(^a\) Negative indicates an improvement in pain

\(^b\) Positive indicates improvement in weakness score

\(^c\) Adverse effects not reported on separately from complete tendon ruptures within study

\(^d\) Measure taken post-operatively only

\(^e\) Level of return to sport not reported
A single retrospective case series investigated the change in outcomes before and after PRP, in those who had failed a multi-modal intervention (physical therapy + non-steroidal anti-inflammatory drugs). Failure was determined by persistence of symptoms and an inability to return to baseline activity after the multi-modal intervention had been completed. There was very low-level evidence of an improvement in symptoms and physical function over time (Table 2). In this study, all athletes who were unable to return to sport with multi-modal intervention alone, returned to sport post PRP plus multi-modal intervention (Figure 4).

Two studies reported change in self-reported symptoms after surgery (Table 2). There was very low-quality evidence of a large reduction in symptoms in the long-term [(−1.89 SPD; 95% CI −2.56, −1.41) to (−6.02 SPD; 95% CI −8.10, −3.94)]. There was very low-quality evidence from a single study of a large improvement in physical function in the long-term (4.08 SPD; 95%CI -5.53 , -2.63). Return to pre-injury level of sport following surgery ranged from 77-100%, with two studies reporting on mean return to sport time to pre-injury level (4.4 to 5 months). One study reported that 88% of participants returned to sport, but did not report whether participants returned to their pre-injury level.

Adverse events were reported in all studies investigating outcomes of surgery (Table 2). Complications occurred in 21 (10%) cases (Table 2). Type and severity of complications varied. Nine patients experienced minor complications. Examples included: notable post-operative soreness and intermittent thigh paraesthesia that resolved spontaneously. Two (1%) patients experienced major complications, which included wound abscess requiring surgical drainage and deep vein thrombosis.

Management of proximal hamstring tendinopathy with corticosteroid injection was described in two studies. Both described change in self-reported symptoms over time (Table 1). One study provided very low-level evidence of clinically significant improvement in self-reported symptoms over time (Table 2). Both studies reported on long-term symptom resolution. One study found that 56% of patients did not experience improvement greater than three months. The other study found that 56% still reported symptoms at long-term follow up. A single study reported on physical function (post-intervention only), as a percentage of full activity, and found activity level increased by 40% in the long-term (mean 24.8 months). No adverse events were reported.

DISCUSSION

The primary aim was to evaluate surgical and non-surgical interventions used to manage proximal hamstring tendinopathy. Three main findings emerged from the systematic review: i) there is a lack of rigorous RCTs comparing treatment interventions, ii) patient selection criteria and use of outcome measures are inconsistent across studies, and iii) there is inadequate description of treatment interventions used.

Of the twelve studies that met inclusion criteria, only two were RCTs. Both were confounded by small sample sizes. There was no high or moderate quality evidence for any intervention (symptoms, physical function or QOL). There was very low-level evidence from a single study to suggest that shockwave therapy was more effective than a multi-modal intervention (exercise, manual therapy, NSAIDs, ultrasound) in professional athletes, at both medium and long-term time points. While there were limitations in completeness of reporting on adverse events, surgery resulted in the highest level of minor and major adverse events.

Injection therapies may be an attractive option because they are less invasive than surgery. While multiple types of injections were reported (platelet-rich plasma, corticosteroid and autologous whole blood), the overall quality of evidence for all injections in proximal hamstring tendinopathy was found to be low or very low (Table 3). Consequently, at this stage it is not possible to recommend any type of injection over another or no injection.

Corticosteroid injections are a commonly prescribed treatment for tendinopathy. While it is important to consider the limitation in overall quality of evidence for corticosteroid injection in this review, the findings in a single group case series indicate a positive change in symptoms over time in the short-term (Table 2). Systematic reviews of high quality RCTs in tendinopathies, which compared corticosteroid injection to other interventions, found a similar trend of a positive short-term effect on symptoms, that are nullified in the medium and long-term. While this early improvement is desirable, it is worth noting that corticosteroid injection has been associated with delayed healing compared to wait and see (lateral epicondylagia) and increased collagen disorganization and necrosis in vitro.

The popularity and cost of regenerative therapies warrants continued research to improve the evidence base. This systematic review found no high or moderate quality evidence for platelet-rich plasma injection; therefore, its utility remains uncertain in this condition. Its effect on symptoms in other tendinopathies was recently summarized in a systematic review. The authors reported that platelet-rich plasma injections were more efficacious than alternative injections on pain severity in tendinopathies (0.47, CI 95% 0.22 to 0.72). However, it is worth noting that there were several limitations, including the type of injections used as comparisons (e.g. corticosteroid injection or saline) and the tendon involved.
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<td>Serious b</td>
<td>Not serious</td>
<td>Serious d</td>
<td>Not serious e</td>
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</tr>
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<td>Not serious</td>
<td>Serious d</td>
<td>Not serious e</td>
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<td>Serious a</td>
<td>Serious b</td>
<td>Not serious</td>
<td>Serious d</td>
<td>Not serious e</td>
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</tr>
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<td>Serious d</td>
<td>Not serious e</td>
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<td>Serious d</td>
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<td>Not serious e</td>
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<td>Not serious e</td>
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<td>Serious d</td>
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<td>No apparent difference between groups</td>
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* ≥ 25% of the participants from studies with a high risk of bias
* Single study (n=300)
* $I^2 > 40$
* Pooled data with < 300 participants for an outcome
* The possibility of publication bias is not excluded, but was not considered sufficient to downgrade the quality of evidence
* No head-to-head comparison
Shockwave therapy has been proposed for a host of upper and lower limb tendinopathies,\textsuperscript{1,41–43,44,45} and other musculoskeletal conditions.\textsuperscript{46,47} This systematic review found preliminary support that shockwave therapy was superior to a multi-modal intervention (exercise, manual therapy, NSAIDs, ultrasound) for improving symptoms and physical function. However, as there was only a single study on shockwave therapy in proximal hamstring tendinopathy, with a small sample size, the results may not be representative of the wider population.\textsuperscript{1} Furthermore, there are several factors that may have made the comparison group (multi-modal intervention) less effective. In this study, exercise was included for three-weeks of the six-week program. In the literature, successful rehabilitation programs for other lower limb tendinopathies consistently report significantly longer time-frames.\textsuperscript{48–50} Avoiding excessive compressive load on the tendon at the enthesis has also been proposed to be a consideration in early to mid-stage exercise selection.\textsuperscript{6,51} In the multi-modal intervention (exercise, manual therapy, NSAIDs, ultrasound), exercises selected likely placed the insertion of the proximal hamstring tendon under high levels of compression, early in rehabilitation (lunge, hamstring stretch, exercise bike).\textsuperscript{1} For further information regarding a management program consistent with these parameters, readers are directed to a narrative review.\textsuperscript{6}

In managing tendinopathy, surgical interventions are typically reserved for recalcitrant cases that have not yet resolved with other interventions. While there were improvements over time following surgery (symptoms and physical function) in case series studies without comparator groups, it is unknown if these are real treatment effects or whether results are caused by other factors, such as natural history or postoperative rehabilitation. An insight into the likely treatment effects of surgery may be gleaned from a recent systematic review of upper and lower limb tendinopathy, which found surgery was not superior to sham surgery or physiotherapy on pain, function, range of motion and success ratings in the longer term.\textsuperscript{52} Recommendations were that surgery should not be seriously entertained until 12 months of an evidence based loading program has been credibly trialled.\textsuperscript{52} Until such time as there are adequately designed comparator studies, these recommendations should also be applied to proximal hamstring tendinopathy.

A limitation of this review was the lack of high-quality trials with consistent patient outcome measures, inclusion criteria and time points. The findings highlight the need for consensus on patient selection criteria, outcome measures and frequency of follow up, to allow the pooling of data. Another limitation was the high number of pre-post study designs. SPDs were calculated in an attempt to provide a standardized measure across study designs. It is important that these SPDs are not misconstrued as treatment effects, because there were no randomized comparisons that remove confounders such as regression to the mean, natural recovery and testing. Consequently, these studies were discussed separately from comparative designs.\textsuperscript{53} Interventions such as load management, heavy slow, strength training, platelet-rich plasma vs placebo and shockwave vs sham shockwave should be avenues for future research. Future research should prospectively report post-surgical protocols and adherence to interventions.

**CONCLUSION**

There was very low-level evidence that shockwave therapy was more effective than a multi-modal intervention. There was very low-level evidence of no difference between autologous whole blood injection and platelet-rich plasma injection. Results of this systematic review highlight the need for high-quality studies and the standardization of selection criteria, outcomes and reporting across studies. This will assist in determining the most effective option for management of proximal hamstring tendinopathy.

**ACKNOWLEDGMENTS**

The authors have no conflicts of interest to declare.

**SOURCE OF FUNDING**

none

Submitted: April 28, 2020 CDT, Accepted: October 10, 2020 CDT
REFERENCES


## APPENDIX

### Table 4: Medline Search

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International Journal of Sports Physical Therapy
Background
Limited ankle dorsiflexion (DF) is associated with ankle sprains and other lower extremity injuries. Current ankle measurements can be laborious to perform in an athletic environment.

Purpose
The purpose of this study was to determine the reliability and discriminant validity of a novel closed-chain ankle DF ROM test, the standing ankle dorsiflexion screen (SADS).

Study Design
Reliability and validity study

Methods
Thirty-seven healthy subjects participated in the study. Two raters measured closed-chain ankle DF range of motion (ROM) using a modified lunge position with an electronic inclinometer. Four raters measured ankle DF using the SADS. Reliability was calculated using intraclass correlation coefficients (ICC) and kappa coefficients for the raters using an electronic inclinometer and the SADS scale, respectively. An independent t-test compared the SADS categories of "behind" and "beyond" to the modified lunge test ROM (p<0.05).

Results
Excellent ICC values (0.95 [95% CI (0.92,0.97)]) and high kappa values were observed (0.61-0.81), with high percent agreement (86-94%). There was a significant difference in ankle DF ROM between the nominally scored "behind" and "beyond" categories, regardless of rater or trial analyzed (behind: 41.3° ± 4.7°; beyond: 51.8°± SD 6.1°, p <0.001).

Conclusions
The SADS was observed to have excellent interrater reliability and high discriminant validity. Furthermore, there was a distinct closed chain ankle DF ROM difference between the "behind" and "beyond" SADS nominal scores.

Clinical Relevance
The SADS can be used as a quick and efficient closed chain ankle DF ROM screen.

Level of Evidence
2b
INTRODUCTION

Athletic lower extremity injuries are common,¹⁻³ with ankle sprains being the most prevalent.³,⁴ Nearly 75% of athletic ankle sprains are recurrent,⁵ burdening the sports medicine provider and health care system.⁵,⁷ Research has suggested that limited ankle dorsiflexion (DF) range of motion (ROM) increases ankle and overall lower extremity injury risk.⁵⁻¹¹ In addition, limited ankle DF is a common injury sequela. Therefore, sports medicine providers have a need for easy to use on-field ankle screens.⁹,¹²

Ankle DF ROM has conventionally been assessed in the open-chain position; however, open-chain ankle testing has poor reliability.¹³ Furthermore, athletic movement and competition are performed in the closed-chain position.¹³,¹⁴ Normal ankle DF allows for lower extremity advancement, running, and proper jump landing.¹¹,¹³ Thus, performing closed-chain ankle measurements allows for more functional clinical testing.¹⁰,¹⁶ Previous closed-chain ankle DF testing has been performed in the half kneeling position¹² and in a modified lunge position both with high reliability and validity.¹⁸,¹⁹ However, these tests require other devices, such as an inclinometer, which are not always readily available.²⁰ This decreases the utility of those tests, as well as the ability of sports medicine providers to effectively and efficiently screen ankle DF. A screen is used to quickly identify if there is a potential problem whereas a measure requires equipment and gives a numerical result. As a result, there is a need for an ankle DF screen that requires minimal equipment and can be implemented quickly and efficiently. Researchers have examined the reliability and validity of a novel ankle DF screen, but used half kneeling dorsiflexion as the referent standard.²¹ Since the ankle dorsiflexion screen is in the standing lunge position, additional analysis comparing measure in that position is warranted.

The purpose of this study was to determine the reliability and discriminant validity of a novel closed-chain DF ROM test, the standing ankle dorsiflexion screen (SADS). It was hypothesized that the SADS would have high reliability and discriminant validity.

METHODS

SUBJECTS

A convenience sample of university students was utilized. Subjects were recruited using fliers on a university campus. To be included in the study, subjects needed to be over 18 years of age and ambulatory without an assistive device. Exclusion criteria consisted of participants with a previous lower extremity orthopedic surgery, current pain or injury, or diagnosed neurological disease. Informed consent was obtained from each subject prior to data collection. The University of Evansville’s Institutional Review Board approved study procedures.

MODIFIED LUNGE ROM MEASUREMENT

The modified lunge position (Figure 1) was used for the discriminant measurement.¹⁸,¹⁹ Closed-chain ankle DF ROM was measured using an electronic inclinometer (Clinometer Android App version 2.4 by Plaincode™ on Samsung Galaxy s9) in a standing modified lunge position with the subjects in a tandem heel to toe stance (Figure 1).¹⁸,¹⁹ For balance, participants held a dowel rod in the contralateral hand. The inclinometer was placed two centimeters below the inferior aspect of the tibial tuberosity on the back lower-limb. Prior to ankle DF testing, subjects were instructed to drop their back knee as far down and forward as possible while taking the back knee as far as possible beyond the back toes, without lifting the back heel. The raters then recorded the dorsiflexion measurement in degrees from tibial vertical for each trial.¹⁷

STANDING ANKLE DORSIFLEXION SCREEN

The SADS was completed using the same position for the modified lunge measurement. The back ankle DF was scored by identifying how far forward the back knee moved in relation to the front medial malleolus. The SADS was scored on an ordinal scale of three categories, behind, within, and beyond (Figure 2).

ANKLE RANGE OF MOTION MEASUREMENTS AND SCREENING

Seven raters were utilized for all measurements; each rater was a physical therapist who specialized in outpatient orthopedics and sports medicine. All raters were trained prior to ankle DF measurements that consisted of demonstration and verbal instruction by an instructor who helped develop the screen and had 20 years of orthopedic physical therapy experience. Following the initial demonstration, each rater
Table 1: Modified Lunge Test Reliability

<table>
<thead>
<tr>
<th></th>
<th>MWLT Kappa CI95†</th>
<th>MWLT % Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rater 1 to Rater 2</td>
<td>.69 (.51-.78)</td>
<td>87</td>
</tr>
<tr>
<td>Rater 1 to Rater 3</td>
<td>.71 (.54-.88)</td>
<td>88</td>
</tr>
<tr>
<td>Rater 1 to Rater 4</td>
<td>.67 (.49-.85)</td>
<td>87</td>
</tr>
<tr>
<td>Rater 2 to Rater 3</td>
<td>.61 (.40-.82)</td>
<td>86</td>
</tr>
<tr>
<td>Rater 2 to Rater 4</td>
<td>.70 (.51-.89)</td>
<td>90</td>
</tr>
<tr>
<td>Rater 3 to Rater 4</td>
<td>.81 (.65-.97)</td>
<td>94</td>
</tr>
</tbody>
</table>

MWLT = Modified Weighted Lunged Test
†CI95 = 95% Confidence Interval

performed at least three trials with feedback from the instructor. This was repeated and compared to the instructors’ measurements until the instructor determined that the measurement was being taken according to the instructions.

Upon arrival of each subject, their age, height, and weight were recorded. Each subject was randomly allocated through a coin flip to first be measured with the modified lunge or SADS. The modified lunge ROM and SADS category measurements were taken two times per ankle with five minutes between measurements to prevent a treatment effect. Two raters measured ankle DF ROM using the modified lunge position. Four raters measured ankle DF via the SADS categories of behind, within, and beyond. All raters were blinded to other rater’s measurements.

STATISTICAL ANALYSES

Descriptive statistics (age, height, weight) were calculated for subjects using means ± standard deviations. Each ankle was analyzed independently. The intraclass correlation coefficient (ICC 2,2) with a 95% confidence interval was used to determine interrater reliability for goniometric ROM measurements where a score of less than 0.40 was deemed poor, 0.40 to 0.59 moderate, 0.60 to 0.74 good, and greater than 0.75 excellent. Kappa coefficients were utilized to determine interrater reliability for the SADS categories, where <0.40 was deemed poor, 0.40-0.59 moderate, 0.60-0.74 good, and >0.75 excellent.

The modified lunge measurements in degrees of dorsiflexion ROM were then averaged between trials. The SADS behind and within categories were dichotomized into one category (behind), while beyond remained the same. Discriminant validity of the SADS categories was assessed with an independent t-test (p<0.05), using the mean values on the modified lunge ROM of the behind and beyond categories. A significant difference in modified lunge ROM between the behind and beyond categories would indicate that the screen can discriminate between individuals with satisfactory ankle dorsiflexion and individuals with limited ankle dorsiflexion. All analyses were conducted in SPSS 24 (IBM SPSS Statistics for Windows, Version 24.0, Armonk, NY: IBM Corp).

RESULTS

The convenience sample consisted of 37 ambulatory subjects (74 ankles), including 27 females (age: 23 ± 1.1 years; height: 167.2 ± 10.2 cm; body mass: 66.9 ± 11.5 kg) and 12 males (age: 22.9 ± 0.7 years; height: 178.3 ± 9.1 cm; mass: 77.6 ±10.3 kg). The interrater reliability was excellent for the modified lunge electronic inclinometer measurements, with an ICC value of 0.95 (95% CI: 0.92-0.97). The kappa coefficient was high for the SADS categories (range: 0.61-0.81), with percent agreement ranging from 86 to 94% (Table 1).

There was a statistically significant difference in closed-chain ankle DF ROM between the behind and beyond cate-
Limited ankle DF is an injury risk factor and common sequela after injury. Many ankle DF measurement techniques are not performed in a standing position and require expensive equipment. Thus, there is a need for an easy to administer ankle screen that requires no equipment. The purpose of this study was to determine the reliability and discriminant validity of a novel closed-chain DF ROM screen, the SADS. Supporting the hypothesis, the SADS was observed to have excellent interrater reliability and discriminant validity. Furthermore, there was a distinct DF ROM difference between the subjects with behind and beyond SADS nominal scores.

The SADS demonstrates discriminant validity. In this study, a digital inclinometer was used. Venturini et al. compared the reliability of ankle DF measurement using both a standard bubble goniometer and a digital inclinometer. The results indicated high (ICC=0.83) interrater reliability for the digital inclinometer and moderate (ICC=0.72) interrater reliability for the bubble goniometer. This corroborates the decision to study the SADS discriminant validity with an inclinometer. A significant difference in modified lunge ROM between the subjects in the behind and beyond categories was observed, though the mean for the behind category was higher than expected.

Using a functional closed-chain position for ankle screening was found to have high reliability compared to the modified lunge tests. This supports previous research in which a functional closed-chain position was found to have the greatest reliability. Munteanu et al. found that ankle DF measurements in a knee extended weight-bearing position had high interrater and intrarater reliability in both novice and experienced raters. Five positions for measuring DF were compared by Krause et al. with the modified lunge having the greatest intrarater (ICC=0.88-0.89) and interrater (ICC=0.82) reliabilities. The authors concluded that the modified lunge position may best assess end-range ankle DF. This highlights the fact that performing an ankle screen in a functional closed-chain position may best assess potential differences in ankle DF ROM.

Closed-chain ankle DF measurements in the modified lunge were similar to previous studies. The SADS behind score mean was 41 degrees. Malliaras et al. found an increased risk of patellar tendinopathy was associated with less than 45 degrees of closed-chain DF in volleyball players. Athletes with repeated ankle sprains have been observed to have decreased ankle DF ROM. The SADS beyond score mean was 51.8 degrees. Driller et al. observed that healthy subjects demonstrated over 50 degrees of ankle DF during the weight-bearing lunge test. Dill et al. found that healthy subjects with normal ankle motion had 51 degrees DF in the weight-bearing lunge position, while limited ankle DF subjects had 39 degrees of ankle DF. In the study previously examining the reliability and validity of the SADS using half kneeling dorsiflexion as the referent standard, there were differences between DF ROM measurements. The half kneeling DF ROM measurements were 33.5 ± 2.0 degrees for behind, 38.6 ± 1.2 degrees for within, and 43.0 ± 0.78 degrees for beyond compared to the standing lunge measurement of behind 41.5° ± 4.7° and beyond 51.8° ± 6.1°. However, the reliability was similar in this study ranging from 0.61 to 0.81 with percent agreement from 86% to 96%.

There were limitations in this study. This study was limited to subjects who were all injury-free at time of testing and were college aged students. However, these participants may have had chronic ankle instability, chronic Achilles tendinopathy, or plantar fasciitis, which may demonstrate long-term ankle or foot impairment. Therefore, the generalization of results outside these ages and to subjects current ankle and/or lower extremity injury is not possible. Further research should include diverse age ranges, sports, and individuals with ankle and/or lower extremity injury to increase external validity. Additionally, prospective studies are required to determine the SADS injury risk identification ability.

CONCLUSION

The SADS is a reliable and valid ankle screen for assessing closed-chain ankle DF ROM. Ankle DF ROM differences between the subjects with SADS nominal scores behind and beyond, were significantly different. The SADS can be used as a quick and efficient closed chain ankle DF ROM screen.

CONFLICT OF INTEREST STATEMENT

Drs. Kiesel and Plisky have equity in Functional Movement Systems LLC who owns the rights to the ankle screen used in this study. Other authors have no conflicts of interest.

ACKNOWLEDGEMENTS

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REFERENCES


Reliability of the Cutting Alignment Scoring Tool (CAST) to Assess Trunk and Limb Alignment During a 45-Degree Side-Step Cut

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Keywords: reliability, movement system, cutting alignment scoring tool, 45-degree side step cutting task

Background

Three-dimensional (3D) motion analysis is considered the gold standard for evaluating human movement. However, its clinical utility is limited due to cost, operating expertise, and lengthy data processing time. Numerous qualitative scoring systems have been introduced to assess trunk and lower extremity biomechanics during functional tasks. However, the reliability of qualitative scoring systems to evaluate cutting movements is understudied. Purpose/Hypotheses: To assess the inter-rater and intra-rater reliability of the Cutting Alignment Scoring Tool (CAST) among sports medicine providers and to evaluate rater agreement of each component of the CAST. The hypotheses were: 1) there would be good–to-excellent inter-rater and intra-rater reliability of the Cutting Alignment Scoring Tool (CAST) among sports medicine providers and to evaluate rater agreement of each component of the CAST. The hypotheses were: 1) there would be good–to-excellent inter-rater and intra-rater reliability among sports medicine providers, 2) there would be good to almost perfect agreement for cut width and trunk lean variables and moderate to good agreement for valgus variables of the CAST.

Study Design

Repeated Measures

Methods

Ten videos of a 45-degree side-step cut performed by adolescent athletes were independently rated on two occasions by six raters (2 medical doctors, 2 physical therapists, and 2 athletic trainers). The variables assessed include trunk lean to the opposite direction of the cut, increased cut width, knee valgus at initial load acceptance (static), and knee valgus throughout the task (dynamic). Variables were scored as either present, which were given a score of “1”, or not present, which were given a score of “0”. Video sequence was randomized in each rating session, and a two-week wash out period was given.

Results

The cumulative inter-rater and intra-rater reliabilities were good (ICC: 0.808 and ICC: 0.755). Almost perfect kappa coefficients were recorded for cut width (k=0.949). Moderate kappa coefficients were found for trunk lean (k= 0.652) and fair kappa coefficients were noted for dynamic and static valgus (k=0.462 and k= 0.533 respectively).

Conclusion

These findings suggest that the CAST is a reliable tool to evaluate trunk and LE alignment during a cutting task by sports medicine providers.
Level of Evidence
Level 2 Diagnosis

INTRODUCTION

Anterior cruciate ligament (ACL) tears are one of the most common injuries reported in the United States with 250,000 cases reported annually.\(^1\) Over the last two decades there has been a rise in ACL injuries in the pediatric and adolescent population, many occurring during sports participation.\(^2\) The mechanism of an ACL injury is commonly classified as contact or non-contact in nature, with the majority of injuries in skeletally immature athletes occurring via a non-contact mechanism.\(^1\)–\(^4\) ACL injury risk in young athletes appears to increase sharply during the growth spurt (12–14 years of age for girls and 14–16 years of age for boys) and peaks shortly after in adolescence.\(^5\) A side-step cutting (change of direction) maneuver performed during sport has been associated with a large proportion of non-contact ACL injuries.\(^6\)–\(^9\) Cutting maneuvers have been analyzed to better understand the mechanism of an ACL tear. Increased knee valgus loads, elevated knee abduction moments, abnormal trunk lateral flexion angles, decreased knee flexion angles, and increased lateral foot plant have been identified as predictors of ACL injury during a cutting task.\(^9\)–\(^12\) In a cross-sectional study of Division 1 Norwegian female handball players, increased cut width, abnormal knee valgus, and toe landing pattern were identified as the strongest predictors of knee abduction moments.\(^11\) In addition, larger medial to lateral distances between the center of mass and center of pressure has been shown to be associated with higher internal knee abduction moments.\(^13\) The aforementioned risk factors were identified with three-dimensional (3-D) motion capture, which is currently considered the gold standard for evaluating human movements.\(^9\)\(^,\)\(^14\)\(^,\)\(^15\) However, equipment cost, operational complexity, and time-consuming data processing requirements make its clinical use impractical. Given the limited availability of 3-D motion capture, two-dimensional (2-D) video analysis has been identified as a clinically relevant alternative. Frontal plane knee valgus angles, measured during a side-step cut and side jump maneuver, were found to have a moderate positive correlation (R\(^2\) = 0.60) with hip internal rotation angles derived from 3-D analysis.\(^16\) Additionally, numerous qualitative scoring systems, based on 2-D videos, have been developed and reported as reliable and valid methods to assess trunk and lower extremity biomechanics during squat and landing tasks.\(^14\)–\(^18\) The Qualitative Analysis of Single Leg Loading (QASLS), was found to have excellent reliability and validity when compared to 3-D motion captured kinematics during single-leg squatting and landing.\(^14\) Similarly, good to excellent reliability was reported for the tuck jump assessment, a repetitive plyometric jump maneuver.\(^17\) The Landing Error Scoring System (LESS) has also been shown to be a reliable and valid tool for identifying high-risk movement patterns during a jump-landing maneuver.\(^18\)

Despite the high percentage of non-contact ACL injuries that occur during cutting tasks, qualitative evaluation tools of cutting movement with 2-D video are substantially limited. Recently, the Cutting Movement Assessment Score (CMAS), a qualitative scoring system, to evaluate a 90-degree cutting maneuver, was introduced.\(^19\) The CMAS was found to be a reliable and valid tool to assess risky movement patterns during a cutting task in college-aged athletes.\(^19\) Additionally, Weir et al assessed the reliability and validity of a 2D video-based screening tool to predict peak knee moments during an unplanned 45-degree side-step cut in a group of junior (age = 15.1 ± 1.2 years) and senior (age = 22.1 ± 2.3 years) elite female field hockey players.\(^15\) In contrast to the CMAS, the screening tool presented by Weir et al involved 2D kinematic measurement of frontal and sagittal plane variables using video analysis software and reported poor to excellent intra-rater and inter-rater reliability.\(^15\) For both levels of athlete, peak trunk lateral flexion, peak hip abduction, knee flexion angle, and trunk flexion ROM were significant predictors of peak knee valgus moments.\(^15\) However, junior and senior athletes demonstrated different movement mechanics.\(^15\) Juniors demonstrated higher dynamic knee valgus and wider foot plant, while seniors showed higher peak trunk lateral flexion, peak hip abduction and knee flexion ROM.\(^15\) These results suggest that pre-adolescent and adolescent athletes may present with different risk profiles during cutting maneuvers than older athletes and thus may benefit from age specific screening tools. To the authors’ knowledge, there have been no studies that assessed a cutting maneuver performed by pre-adolescent and adolescent athletes using a qualitative scoring system. Given the sharp increase in ACL injury risk in children ages 12-15, there is a need for available screening tools to identify risky movement patterns in this age group.\(^3\) Additionally, no qualitative assessment tool for evaluating a 45-degree cutting movement was found. Biomechanical demands during cutting and change of direction maneuvers have previously been described as being angle dependent, with differences in knee joint loading and technique found between 90 degree and 45 degree cut directions.\(^20\)\(^\,\)\(^21\) Furthermore, when implementing cutting technique modification training, clinicians and coaches need to be cognizant of the potential impact on performance. Sagittal plane mechanics have been found to predict performance of the 45-degree cut task, while frontal plane mechanics predicted performance of the 90-degree cut task.\(^21\) Given that frontal plane variables are most predictive of high knee abduction moments, technique training during a 90-degree cutting task that aims to address frontal plane variables may have the potential to negatively impact cutting performance.\(^22\) This may have implications for injury risk screening and targeted movement pattern correction as coaching staff may be less likely to adopt screening and training interventions that may negatively influence performance. Having identified a gap in qualitative scoring analysis for pre-adolescent and adolescent athletes, the authors of this study developed a qualitative scoring system, the Cutting Alignment Scoring Tool (CAST), to evaluate LE alignment and trunk movement during a 45-degree side-step cut. The central purpose of this study was to examine the reliability of the CAST among various sports medicine providers including medical doctors, physical therapists,
and athletic trainers. This study consisted of two aims: 1) to assess the inter-rater and intra-rater reliability of the CAST among sports medicine providers, and 2) to evaluate rater agreement of each component of the CAST. The hypotheses were: 1) there would be good–to-excellent inter-rater and intra-rater reliability among sports medicine providers, 2) there would be good to almost perfect agreement for cut width and trunk lean variables and moderate to good agreement for valgus variables of the CAST.

METHODS

STUDY DESIGN

A repeated measures study design was used. To achieve the primary aim of the study, inter-rater and intra-rater reliability were calculated based on the 1st and 2nd reliability sessions. The study protocol was developed based on the Declaration of Helsinki and ethical standards in sport and exercise science research.23 Institutional Review Board approval was obtained prior to commencement of the study.

PARTICIPANTS

A total of 8 adolescent athletes (5 males, 3 females, age=14.7 ± 1.2 years, height=165.6 ± 8.4cm, mass = 62.6 ± 3.3kg) were recruited from local high school and club sport teams. Inclusion criteria were: 1) age between 12 and 17 years and 2) active participation in sports requiring cutting and pivoting in the last 12 months. The following exclusion criteria were used: 1) LE injury within 6 months, 2) past history of LE surgery, 3) a positive response on the Physical Activity Readiness Questionnaire for Everyone (PAR-Q+), and 4) history of scoliosis. The PAR-Q+ was used to determine the participant’s readiness and safety for physical activity. A positive response of the PAR-Q indicates the need to seek further advice from a physician prior to engaging in physical activity.24 All participants provided written informed consent, and their parents or legal guardian provided signed consent. Data collection was performed in a Sports Medicine laboratory at a local University.

DATA COLLECTION

Prior to performing the 45-degree side-step cut task, a 5-minute warm up on a cycle ergometer (Star Trac Inc, Irvine, CA) was performed. Participants practiced the side-step cutting maneuver 3 times in each direction or until they felt comfortable with the procedure. They were instructed to sprint at 80% of their maximum speed in a forward direction toward the “opponent cone”, to plant, and perform the side-step cut maneuver. (Figure 1).

This procedure was modeled by a testing protocol described by McLean et al.16 Specifically, participants decelerated, planted on the right foot, and performed a side-step cut, running in the left direction between cones placed along a 45-degree line of progression. The procedure was repeated planting on the left foot and running to the right direction (Figure 1). Participants then completed three trials planting on the right LE and three trials planting on the left LE, with a trial considered “good” if the subject’s foot landed within the stance/pivot area necessary for successful completion of the task. The testing order was standardized for all participants for ease of set up. Video data were collected with an iPad (iOS 12.4.1) with a frame rate of 30 frames per second. The IPad was mounted on a tripod and placed at a distance of 3.7 m in front of the force plates at a height of 0.86 – 0.96m. Participants performed a total of 6 cutting maneuvers. All videos were processed and slowed by 50% for visual analysis. All participants’ faces were blurred using Adobe Premiere Pro.

A clinically established checklist, CAST, was developed to examine the quality of trunk and LE movement during the cutting maneuver based on 2-D video. The checklist was devised based on previously reported movement screening systems.14,25,26 It involves a dichotomous rating system, with scoring defined as “1” when a movement fault was present and “0” when optimal movement patterns were observed. Variables evaluated in the CAST include; trunk lean to the opposite direction of the cut, increased cut width, knee valgus at initial load acceptance (Static Evaluation), and knee valgus throughout the cutting task (Dynamic Evaluation). The CAST checklist is shown in Table 1.

RATERS

The primary goal in choosing raters was to evaluate inter- and intra-rater reliability among sports medicine providers. Six raters consisting of two medical doctors (pediatric orthopedic surgeons), two physical therapists, and two athletic trainers were recruited for participation in this study. Raters were chosen because of their primary role in providing clinical care to young athletes in a pediatric healthcare system. The raters independently viewed a total of 10 videos. All raters provided their consent to participate in the current study.

Figure 1: 45-degree side step cut task

International Journal of Sports Physical Therapy
Table 1: Cutting Alignment Scoring Tool (CAST)

<table>
<thead>
<tr>
<th>Item</th>
<th>Operational Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Trunk lean to opposite direction of cut</td>
<td>At the time point of initial load acceptance, if the whole trunk segment appears to be deviated greater than 10 degrees from a horizontal line through the hips (ASIS* to ASIS*) score 1 (YES). If not, score 0 (NO).</td>
</tr>
<tr>
<td>2. Increased cut width</td>
<td>At the time point of initial load acceptance, draw a line down from the lateral most aspect of the athlete’s stance leg hip, if the line appears to fall more than one shoe width, medial to the foot score 1 (YES). If not, score 0 (NO).</td>
</tr>
<tr>
<td>3. Knee Valgus at Initial load acceptance (Static Evaluation)</td>
<td>At the time point of initial load acceptance, if the weight bearing limb demonstrates valgus (thigh adduction, genu valgum, or knee abduction) score 1 (YES). If the weight bearing limb is in neutral alignment score 0 (NO).</td>
</tr>
<tr>
<td>4. Knee Valgus throughout the cutting task (Dynamic Evaluation)</td>
<td>During the cutting task if the weight bearing limb demonstrates valgus (thigh adduction, genu valgum or knee abduction) score 1 (YES). If the weight bearing limb is in neutral alignment, score 0 (No).</td>
</tr>
</tbody>
</table>

*ASI**= Anterior Superior Iliac Spine

PROCEDURES

The 10 videos were randomly selected from the six trials performed by the eight participants. A review of the available studies that had a similar study objective led to the current sample size selection. Video trials from three participants performing the side-step cut planting on the right limb were used, trials of five participants performing the side-step cut on the left limb were used and, for 1 participant both limbs were used. The videos were slowed to 50% speed and were provided to each rater with brief instructions and a preliminary version of the CAST. The raters were instructed to view the videos independently without communicating with one another. They were allowed to review the videos as many times as necessary and could pause the video as needed. Raters were not permitted to make any marks on the screen, including joint angle or distance-based measurements.

The raters were given one week to view and score the videos. After the initial scoring, a peer-to-peer discussion was held to discuss the CAST rating tool and to develop detailed definitions to improve the interpretation of the scoring criteria. The discussion was performed via a two-hour long video conference. During the video conference, each of the 10 videos were displayed, and each rater had an opportunity to share their clinical diagnosis of at-risk movements. After each rater provided their interpretation of at-risk movements and discussed subsequent clinical decision-making, the group provided feedback. After the peer-to-peer discussion, a reference sheet (Figure 2) was developed, and the CAST scoring criteria was finalized (Table 1).

The first reliability session was performed one-week following the interactive peer-to-peer discussion. The same reviewing instructions that were used during the development of the CAST scoring criteria were given to each rater and the importance of the independent reviewing process was emphasized. The first reliability session consisted of the same 10 videos, with sequences altered in random order to minimize memory bias. After the first reliability session, a two-week break was given as a wash-out period. Next, the second reliability session was performed, using the same method outlined for the first reliability session. The sequence of videos was further randomized in the second reliability session.

STATISTICAL ANALYSIS

Reliability was determined by calculating intraclass correlation coefficients (ICC) for the CAST total scores, with 2-way mixed-effects model and their 95% confidence intervals (95% CIs) for inter-rater and intra-rater reliability. For the first aim, the individual and cumulative inter-rater reliability of six raters were calculated within the 1st and 2nd reliability sessions. The individual and cumulative intra-rater reliability of six raters were calculated between the 1st and 2nd reliability sessions. ICC values less than 0.50, between 0.50 and 0.75, between 0.75 and 0.90, and greater than 0.90 were defined as poor, moderate, good and excellent reliability, respectively. To achieve study aim 2, a kappa coefficient was calculated for each of the checklist variables using the formula; $k = Pr(a) – Pr(e)/1 – Pr(e)$, where $Pr(a)$ is equal to the relative observed agreement between raters and $Pr(e)$ is equal to the hypothetic probability of chance agreement. The kappa coefficient was interpreted based on the scale of Landis and Koch with 0.01-0.2 being slight, 0.21-0.4; fair, 0.41-0.6; moderate, 0.61-0.8; good and 0.81-1.0 almost perfect. All statistical analyses were conducted using SPSS Statistics 22 (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp).

RESULTS

Inter-rater reliability for the 1st reliability session was moderate (ICC: 0.632, 95% CI 0.100-0.895) and inter-rater reliability for the 2nd reliability session was excellent (ICC: 0.901, 95% CI 0.766-0.971). The cumulative inter-rater reliability, a combination of 1st and 2nd inter-rater reliability, was good (ICC: 0.808, 95% CI 0.644-0.913). Intra-rater reliability of each rater is depicted in Table 2. The cumulative intra-rater reliability of the six raters was good (ICC: 0.755, 95% CI 0.588-0.852). Kappa-coefficients for each variable are presented in Table 3. Almost perfect kappa coefficients were recorded for cut width (k=0.949). Moderate kappa coefficients were found for trunk lean (k= 0.632), and fair
kappa coefficients were noted for dynamic valgus and static valgus (k = 0.462 and k = 0.533 respectively).

**DISCUSSION**

The primary purpose of this study was to assess the within session inter-rater reliability and the between session intra-rater reliability of the CAST. The CAST demonstrated good inter-rater reliability (cumulative ICC: 0.808, 95% CI 0.644-0.913) and good intra-rater reliability (cumulative ICC: 0.753, 95% CI 0.588-0.852). These findings supported our hypotheses that the CAST would demonstrate good-excellent inter-rater and intra-rater reliability among sports medicine providers. The findings also suggest that the CAST may allow clinicians to standardize their assessment of trunk and lower extremity alignment using 2-D video during a cutting task. It needs to be noted, however, that when comparing the first and second inter-rater reliability sessions, the first session showed lower reliability and larger confidence intervals relative to the second session (ICC: 0.632, 95% CI 0.100-0.895). The improvement in reliability from the first to the second session may have potentially been the result of a learning effect as this was the third time the raters viewed the same 10 videos. Interestingly, the medical doctors demonstrated the highest intra-rater reliability (Table 2). This contrasted with the authors’ expectations. Initially, it was speculated that the physical therapists and athletic trainers would show the highest intra-rater reliability due to their frequent use of movement analysis in their daily practice settings. One explanation for this outcome may be certain character traits that are unique to the medical doctor profession. Anecdotally, medical doctors are trained to adhere to medical guidelines to make precise and informed decisions in their clinical settings, especially during surgery. Both medical doctors in this study were orthopedic surgeons, which might have contributed to the higher intra-rater reliability. The findings of the current study are generally in agreement with the work of Dos’ Santos et al. who found moderate inter-rater reliability (ICC = 0.690) and excellent intra-rater reliability (ICC = 0.946) when utilizing a similar qualitative scoring system to evaluate a 90 degree cutting maneuver. There are several differences in study design. Dos’ Santos et al determined inter-rater reliability of the CMAS using three raters rather than six. Despite a larger number of raters, inter-rater reliability of our measurement tool, the CAST, was higher than
Table 2: Intra-rater reliability (ICC, 95%CI, cumulative values) of 6 raters

<table>
<thead>
<tr>
<th>Raters</th>
<th>ICC*</th>
<th>95% CI</th>
<th>Cumulative Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD #1</td>
<td>0.682</td>
<td>-0.432, 0.923</td>
<td></td>
</tr>
<tr>
<td>MD #2</td>
<td>0.910</td>
<td>0.641, 0.978</td>
<td></td>
</tr>
<tr>
<td>Physicians</td>
<td></td>
<td></td>
<td>0.824 (0.551,0.931)</td>
</tr>
<tr>
<td>PT #1</td>
<td>0.640</td>
<td>-0.578, 0.912</td>
<td></td>
</tr>
<tr>
<td>PT #2</td>
<td>0.857</td>
<td>0.396, 0.965</td>
<td></td>
</tr>
<tr>
<td>Physical Therapists</td>
<td></td>
<td></td>
<td>0.776 (0.426,0.912)</td>
</tr>
<tr>
<td>AT #1</td>
<td>0.589</td>
<td>-0.653, 0.898</td>
<td></td>
</tr>
<tr>
<td>AT #2</td>
<td>0.780</td>
<td>0.116, 0.945</td>
<td></td>
</tr>
<tr>
<td>Athletic Trainers</td>
<td></td>
<td></td>
<td>0.656 (0.157,0.862)</td>
</tr>
<tr>
<td>Cumulative ICC* of all 6 raters</td>
<td></td>
<td></td>
<td>0.753 (0.588,0.852)</td>
</tr>
</tbody>
</table>

ICC* = intraclass correlation coefficient, CI = confidence interval, MD = medical doctor, PT = physical therapist, AT = athletic trainer

Table 3: Inter-rater reliability for Cutting Alignment Scoring Tool (CAST) variables

<table>
<thead>
<tr>
<th>Raters</th>
<th>Cut Width (k)</th>
<th>Trunk Lean (k↑)</th>
<th>Dynamic Valgus (k)</th>
<th>Static Valgus (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD #1</td>
<td>1.000</td>
<td>0.582</td>
<td>0.600</td>
<td>1.000</td>
</tr>
<tr>
<td>MD #2</td>
<td>1.000</td>
<td>0.737</td>
<td>0.600</td>
<td>(-) 0.379</td>
</tr>
<tr>
<td>PT #1</td>
<td>1.000</td>
<td>0.412</td>
<td>0.400</td>
<td>0.600</td>
</tr>
<tr>
<td>PT #2</td>
<td>1.000</td>
<td>0.412</td>
<td>0.091</td>
<td>1.000</td>
</tr>
<tr>
<td>AT #1</td>
<td>1.000</td>
<td>0.449</td>
<td>0.200</td>
<td>0.583</td>
</tr>
<tr>
<td>AT #2</td>
<td>0.737</td>
<td>0.615</td>
<td>0.800</td>
<td>1.000</td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.949</td>
<td>0.632</td>
<td>0.462</td>
<td>0.533</td>
</tr>
</tbody>
</table>

k = kappa coefficient, MD = medical doctor, PT = physical therapist, AT = athletic trainer

that of the CMAS. The underlying reason for higher inter-rater reliability found in the current study is likely multifactorial. One potential explanation for the observed higher inter-rater reliability in the study is the interactive peer-to-peer discussion. During the discussion session, all raters openly shared their clinical knowledge, expertise, and experiences. The reference sheet and CAST were developed as an output of the discussion. This process provided an opportunity for sports medicine providers from multiple disciplines to critically review the scoring tool and contribute to the final development. Hence, discussion among peers may be an important step to develop a clinically useful evaluation tool. This lesson also has an important clinical implication, particularly in a multi-center study setting. Reviewing a protocol, images, or variables of interests prior to study commencement is likely helpful to enhance reliability among peers. Another notable difference between this study and that of the CMAS is that the intra-rater reliability of the CMAS was reported for only one rater. The current study reported the average of six raters which may have contributed to the lower intra-rater reliability. Lastly, Dos’ Santos et al only used a one-week washout period compared to a two-week washout period used in the current study. There are also several differences in the variables evaluated with the CMAS compared to those evaluated with the CAST. The variables evaluated with the CMAS are observed through three different camera views in the frontal, sagittal and 45-degree planes. The variables assessed in the current study were only observed through one camera view which is in the frontal plane. Frontal plane variables were chosen based on the work of Imwalle et al who found that increased knee abduction moments during cutting predominantly stem from the frontal plane. Although the three-camera views used in the CMAS likely allowed for improved identification of the variables of interest, obtaining multiple views of a cutting maneuver on the field may pose challenges. A single view assessment tool may result in improved adoptability by clinicians and coaching staff. Additionally, eight variables are evaluated with the CMAS while only four variables are evaluated with the CAST. The lower number of variables assessed with the CAST may have improved the tools efficiency, however, future studies are necessary to determine its validity against 3D motion capture, and in identifying athletes displaying high risk cutting mechanics.

The second aim of this study was to evaluate rater agreement of each component of the CAST. Almost perfect kappa coefficients were found for cut width (k=0.949) while moderate kappa coefficients were observed for trunk lean (k=0.652) and fair kappa coefficients were noted for dynamic
valgus and static valgus (k=0.462 and k=0.553 respectively). The results suggested that assessments of less complex movements during a cutting maneuver were more reliable than multiplanar movements. This supports the hypothesis that there will be good to almost perfect agreement for cut width, and moderate to good agreement for trunk lean. The hypothesis that valgus variables would demonstrate moderate to good agreement was not supported. Only fair agreement was found for dynamic and static valgus. Again, these findings were generally in agreement with Dos Santos et al who found fair agreement (k=0.551) for frontal plane trunk position and moderate agreement (k=0.605) for excessive knee valgus motion. Several factors may have contributed to the decreased reliability of valgus identification in the current study. For example, changes in knee flexion angle and deviation of the plane of the body out of the frontal plane of the video camera may make it difficult to accurately identify frontal plane movement faults. Additionally, videos in this study were collected on an iPad at a rate of 30 frames per second, future studies should determine if video collection at a higher frame rate would increase the reliability of the CAST. Future studies are warranted to consider those aspects in conjunction with cutting maneuvers, which should help in identifying at-risk movements with 2-D video analysis.

The authors recommend that future studies should also aim to determine the predictive validity of qualitative and 2-D screening tools for ACL injury risk. In a prospective study by Hewett et al, knee abduction moments predicted ACL injury with 73% specificity and 78% sensitivity and dynamic valgus measures showed a high predictive value ($r^2=0.88$). Screening tools that are able to accurately identify high knee abduction moments and dynamic valgus values may be the most effective in identifying athletes at increased risk for an ACL injury. A statistically significant strong relationship ($r = 0.796$, 95% CI 0.647 to 0.887) was found between the CMAS and peak knee abduction moments in a sample of 41 college aged athletes (28 males/13 females, mean age 21.3 ± 4.0 years) from multiple sports. These finding suggest that a qualitative assessment of a cutting task may help identify collegiate athletes with high knee abduction moments during a cutting maneuver. Similarly, moderate correlations were found between 2-D measurement of frontal plane valgus angles and 3-D analysis ($r^2=0.58$), suggesting its feasibility for ACL injury risk screening. Future studies should continue to explore this area, specifically in the pre-adolescent and adolescent populations, which have been understudied. It is currently unknown if qualitative screening tools evaluating cutting technique in young athletes are predictive of ACL injuries. With this concept, the current study focused on pre-adolescent and adolescent population. The dynamic and static cumulative inter-rater reliabilities were not as high as was anticipated (ICC=0.462, 0.533, Table 3). Specific bony landmarks and/or more stringent definitions of knee valgus in cutting maneuvers may need to be addressed by sports medicine providers. The development of screening tools that are able to accurately identify high-risk cutting movements may provide coaches and practitioners with an efficient and effective strategy to screen young athletes for ACL injury risk. Furthermore, providing clinicians with a practical tool to evaluate cutting tasks may enhance injury prevention interventions. Given the high percentage of ACL injuries that occur during a cutting or pivoting mechanism, future research is warranted to find an association between clinically useful 2-D video analysis and ACL injury in young active populations.

LIMITATIONS

Several limitations must be stated. First, the CAST only evaluates frontal plane movements. Cutting maneuvers are multiplanar and incorporating additional views and planes may improve the capacity to identify faulty movement biomechanics. Additionally, the operational definitions for each variable were written with varying criteria. For example, an approximate degree reference was provided for trunk lean, a body reference was provided for cut width and a qualitative description was provided for the valgus variables. This variability may have contributed to rater confusion when using the tool. Another limitation is that only the reliability of sports medicine providers was evaluated. Sport specific coaches spend the most time working with athletes; thus, determining the reliability of the CAST amongst coaches may greatly increase its utility. In this study a peer-to-peer discussion was held with all six raters, one week prior to the first reliability session. During this discussion the same 10 videos that were used in the 1st and 2nd reliability sessions were viewed and discussed as a group. Despite the use of a two-week wash out period between rounds and the randomization of videos in each round, this discussion may have increased the intra-rater and inter-rater reliability of the tool. Future studies should evaluate the reliability of the CAST without the added discussion. It should also be acknowledged that this study used a planned cutting task. Different outcomes may be expected with the use of an unplanned cutting task which has been shown to result in greater knee joint loads when compared to planned cutting maneuvers. Lastly, it is unknown if the CAST is a valid tool for predicting ACL injury risk during a cutting maneuver. It is important to investigate whether or not 3-D kinematic variables are correlated with visually identified movements. Future studies should aim to determine its predictive validity and its criterion validity with 3-D motion capture.

CONCLUSION

Despite limitations, this study demonstrated that the CAST, a qualitative evaluation tool to identify at-risk movements for ACL tear during a side-step cutting task, demonstrated good inter-rater and intra-rater reliability among sports medicine providers. It also showed almost perfect agreement for cut width, moderate agreement for trunk lean, and fair agreement for knee valgus variables. The two-hour peer-to-peer discussion might have contributed to the relatively high inter-rater reliability. These findings suggest that the CAST can be used as a reliable tool to evaluate trunk and lower extremity alignment during a cutting task by sports medicine providers. Identification of risky movement patterns may serve as a starting point for sports medicine providers to provide targeted technique.
training to reduce ACL injury risk during cutting tasks. Future work is recommended to determine the predictive validity of the CAST in identifying individuals at risk for ACL injury.

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No funding

APPROVAL

This study was approved by the University of Miami and Western International Review Board for human subjects' research.

FINANCIAL DISCLOSURE AND CONFLICT OF INTEREST

The authors affirm that they have no financial affiliation (including research funding) or involvement with any commercial organization that has a direct financial interest in any matter included in this manuscript, except as disclosed in an attachment and cited in the manuscript. Any other conflict of interest (i.e., personal associations or involvement as a director, officer, or expert witness) is also disclosed in an attachment.

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Examining Muscle Activity Differences During Single and Dual Vector Elastic Resistance Exercises

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1 Department of Kinesiology, Brock University

Keywords: upper limb, theraband, rehabilitation, electromyography, biomechanics

Background
Elastic resistance exercise is a common part of rehabilitation programs. While these exercises are highly prevalent, little information exists on how adding an additional resistance vector with a different direction from the primary vector alters muscle activity of the upper extremity.

Purpose
The purpose of this study was to examine the effects of dual vector exercises on torso and upper extremity muscle activity in comparison to traditional single vector techniques.

Study Design
Repeated measures design.

Methods
Sixteen healthy university-aged males completed four common shoulder exercises against elastic resistance (abduction, flexion, internal rotation, external rotation) while using a single or dual elastic vector at a fixed cadence and standardized elastic elongation. Surface electromyography was collected from 16 muscles of the right upper extremity. Mean, peak and integrated activity were extracted from linear enveloped and normalized data and a 2-way repeated measures ANOVA examined differences between conditions.

Results
All independent variables differentially influenced activation. Interactions between single/dual vectors and exercise type affected mean activation in 11/16 muscles, while interactions in peak activation existed in 7/16 muscles. Adding a secondary vector increased activation predominantly in flexion or abduction exercises; little changes existed when adding a second vector in internal and external rotation exercises. The dual vector exercise in abduction significantly increased mean activation in lower trapezius by 25.6 ± 8.11 %MVC and peak activation in supraspinatus by 29.4 ± 5.94 %MVC (p<0.01). Interactions between single/dual vectors and exercise type affected integrated electromyography for most muscles; the majority of these muscles had the highest integrated electromyography in the dual vector abduction condition.

Conclusion
Muscle activity often increased with a second resistance vector added; however, the magnitude was exercise-dependent. The majority of these changes existed in the flexion and abduction exercises, with little differences in the internal or external rotation exercises.

Level of Evidence
3b

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INTRODUCTION

The shoulder complex is a mobile arrangement of joints and surrounding tissues which lends itself to a wide range of injury possibilities. The glenohumeral joint is one of the most mobile and inherently unstable joints in the human body due to its overall structure. With only surrounding musculature and the shallow glenoid fossa available to maintain control during motion, the glenohumeral joint is prone to injuries such as dislocations, impingement, subluxations, rotator cuff tears and tendinosis. Injuries to the shoulder complex account for approximately 10% of all athletic injuries. In particular, overhead sport athletes such as swimmers, tennis, volleyball and baseball players consistently place high tissue loads on the shoulder, and are often susceptible to injury. In order for an athlete or occupational worker to recover and return to work at peak performance, it is critical that the rehabilitation process target an optimized recovery plan such that the individual can return with a high level of strength and mobility.

Shoulder rehabilitation requires a multi-faceted approach. Rehabilitation programs can be complicated due to the need to balance the strength, flexibility and stability required on an individualized basis. One component of many shoulder rehabilitation programs is to use elastic resistance bands for resistance training, as they are inexpensive, versatile, adaptable and an effective way to incorporate external resistance. Elastic resistance has been demonstrated to promote increased shoulder strength, stability, and mobility. After training three times a week for six weeks using elastic resistance, collegiate baseball players showed a 20% increase in eccentric shoulder rotator muscle torque. Incorporating elastic resistance has also been demonstrated to increase shoulder muscle strength in competitive youth swimmers and elite-level tennis players, as well as increased throwing velocities in elite female handball players.

Shoulder rehabilitation often focuses on increasing muscle activation of targeted musculature. The primary research in this area involves resistance exercises of single-joint, uniplanar exercises that implement dumbbells or free weights to generate external resistance. However, a smaller number of studies have examined activation of shoulder musculature during rehabilitation using elastic bands and tubing, and these studies typically involve clinical populations or a small number of muscles. Using elastic bands can provide advantages in rehabilitation over free weights, as they provide increased control over phases of the movement, can act independent of gravity, and can easily modify resistance by adjusting the stretch. This elastic resistance provides similar muscle activation as isoinertial resistance, allowing relatively equal muscle adaptations between these two modes of exercise.

Despite the prevalence and effectiveness of traditional elastic resistance rehabilitation and strengthening programs, little research has been conducted on dual vector exercises. Traditional work has focused on a single elastic resistance vector oriented to target the muscle of interest. This elastic generates loading through tension along the line of the elastic, and introducing a second elastic vector (dual vector) at a different location generates isotonic resistance in a direction other than gravity, altering the loading characteristics in rehabilitation programs. Dual vector exercises use additional lines of elastic loading to create forces in multiple directions. However, whether these modifications better target muscles of interest or alter activation beyond the primary muscle is unknown. The purpose of this study was to examine the effects of dual vector exercises on torso and upper extremity muscle activity in comparison to traditional single vector techniques. It was hypothesized that dual vector exercises would increase muscle activity compared to single vector exercises regardless of exercise selection.

METHODS

This study employed electromyography during elastic resistance exercises. Study design consisted of participants completing eight different testing conditions comprised of four single and four dual vector elastic resistance exercises on a single day, with each condition completed twice. Bipolar surface electrodes recorded muscular activation of 16 muscles surrounding the right torso and right upper extremity as participants completed shoulder rehabilitation exercises using single or dual vector resistance. Post-collection processing assessed changes in muscular activation across exercises and elastic resistance conditions.

PARTICIPANTS

Sixteen right-handed male subjects [22.4 ± 1.6 years, 1.81 ± 0.07 m, 82.1 ± 8.6 kg] participated after providing informed consent. Sample size was determined a priori using G*Power 3.1.9.7 (Universität Düsseldorf, Düsseldorf, Germany) and using effect sizes from previous elastic resistance literature. Exclusion criteria included shoulder, elbow, wrist or back pain or injury within the past 12 months. This study was approved by the institutional Research Ethics Board (BREB-17-346).

INSTRUMENTATION

Surface electromyography (EMG) was recorded from 16 right (dominant side) muscle sites (Figure 1): anterior, middle and posterior deltoid, clavicular and sternal heads of pectoralis major, serratus anterior, biceps, triceps, latisimus dorsi, flexor digitorum superficialis, extensor digitorum, supraspinatus, infraspinatus, and upper, middle and lower trapezius. After shaving the skin with a razor and cleansing with alcohol to minimize impedance, bipolar Ag-AgCl surface electrodes (MediTrace 130, Kendall, Mansfield, MA, USA) were placed over the belly of each muscle based on published guidelines. A ground electrode was placed over the medial clavicle. EMG signals were sampled at 2160 Hz and collected using a Bortec AMT-8 EMG system (Bortec Biomedical Ltd, Calgary, AB, Canada). Raw EMG signals were band-pass filtered from 10 to 1000 Hz and differentially amplified using a common-mode rejection ratio > 100 dB with input impedance of ~10 GΩ.
EXPERIMENTAL DESIGN

The eight experimental conditions consisted of four different exercises (shoulder abduction, flexion, internal rotation, external rotation) completed using either single or dual vector elastic resistance. Elastic resistance was completed using Theraband® CLX (Performance Health, Akron, OH, USA). Theraband® CLX consists of elastic bands in fused links throughout the length of the elastic, allowing loops at various lengths as well as multiple connection points to the body within a single band.

PROTOCOL

The protocol included application of surface electrodes, collection of maximum voluntary contractions (MVCs), a training period and experimental trials. Following electrode placement, participants completed five second muscle specific MVCs resisted by a researcher who had extensive experience with generating effective MVCs, with each muscle completed twice.30 A minimum of one minute of rest was provided between contractions and participants received verbal encouragement during MVCs.31,32 Following MVCs, all experimental conditions were explained verbally and demonstrated by the researcher, then participants had time to practice each condition to ensure proper technique. Participants self-selected elastic resistance level; participants were instructed to choose a resistance level that would allow them to complete 12-15 continuous repetitions without fatigue.33 All participants chose either the green or blue elastic resistance bands (2.1 and 2.6 kg at 100% elongation, respectively), which are intermediate band colors and appropriate resistances for shoulder exercises.22 All exercises for a participant were done with the same color bands at the same length, and each exercise began with the band at 125% elongation.29

Four elastic rehabilitation exercises were evaluated (Figure 2 and 3). Participants completed these exercises using their right arm. These exercises included: 1) shoulder abduction - arm motion from 0° to maximal elevation in the coronal (abduction) plane with the resistance anchored between the foot and hand, 2) flexion - arm motion from 0° to maximal elevation in the sagittal plane with the resistance anchored between the foot and hand, 3) internal and external rotation, where internal and external rotation required the arm in the frontal plane and the humerus at 90° of arm elevation with the elbow in 90° of flexion;20 resistance was anchored to a fixed surface in front of the participant at shoulder height. Each exercise required the participants to hold the elastic resistance band in their right hand. The dual vector was placed such that this vector was parallel to the ground at the height of the elbow in internal and external rotation tasks, and in line with the mediolateral axis of the elbow in flexion and abduction tasks. Participants were instructed to keep their elbow straight during flexion and abduction trials, and to maintain a 90° elbow angle in the external rotation trials. Motion was visually inspected during trials by two researchers in different planes (front, right side) to ensure proper technique. If a participant did not maintain the required technique during collection the participant was provided feedback and the trial was recollected.

Internal and external rotation dual vector exercises were completed with one elastic resistance band held in the hand, and an additional elastic band looped over the elbow. The elastic resistance was mounted to a fixed surface such that the vector at the elbow was parallel with the floor at approximately shoulder height (Figure 3B, 3D). Abduction and flexion dual vector exercises had two bands held in the hand while the second vector added resistance in a perpendicular plane to the motion (Figure 2B, 2D). In each exercise, participants completed three repetitions at a fixed cadence of two seconds per repetition, one second concentric, one second eccentric as informed by a metronome at 60 bpm. Participants completed two sets for all conditions in a fully randomized order, with a minimum of one minute of rest between exercises.

DATA ANALYSIS

EMG was analyzed with respect to amplitude. MVC and experimental data were processed identically. Raw EMG signals were high-pass filtered at 30 Hz to eliminate ECG contamination.34 These data were then full-wave rectified and linear enveloped using a dual-pass fourth-order low-pass Butterworth filter at 4 Hz. Mean, peak and integrated EMG via trapezoidal integration (iEMG) was calculated for each muscle from each set of exercises and normalized to the single highest peak of the two muscle-specific MVC trials.

STATISTICAL ANALYSIS

Statistical analysis was focused on muscle activation changes from differing exercises and the use of single or dual elastic resistance. Dependent variables included mean, peak and integrated EMG for each of the 16 muscles in all
eight conditions (four exercises, two elastic resistance settings). Prior to statistical analysis, a Shapiro-Wilk test was completed for each dependent variable to examine normality; in all cases, the null hypothesis was retained. A 2-way repeated measures ANOVA with 2 independent factors (exercise, number of elastic resistance vectors) with one 2-way interaction examined muscle activity changes. Statistical significant was set at $\alpha = 0.05$. Tukey HSD post-hoc and t-tests were performed to examine statistically significant main effects and interactions. All statistical analyses were completed using JMP 14.0 (SAS Institute, North Carolina, USA).

RESULTS

All independent variables differentially influenced mean, peak, and integrated muscle activation as interactions or main effects. This results section has been subdivided by dependent variable.

MEAN ACTIVATION

Interactions between exercise and single/dual resistance vectors affected mean EMG for most muscles, while those that did not display interactions demonstrated main effects. Interactions existed in the anterior, middle and posterior deltoid, sternal and clavicular heads of pectoralis major, triceps, supraspinatus, infraspinatus, and upper, middle and lower trapezius ($p < 0.001$ to 0.022) (Table 1). The dual vector abduction exercise generated the highest mean EMG in middle deltoid, posterior deltoid, triceps, supraspinatus, infraspinatus, upper trapezius, middle trapezius, and lower trapezius, with mean values ranging from 9.41-77.6 %MVC, while the dual vector flexion exercise generated the highest mean EMG in the anterior deltoid and latissimus dorsi at 25.78 ± 1.37 and 14.22 ± 1.74 %MVC, respectively (Table 1). Activation across muscles was typically highest in the flexion or abduction exercises, and internal rotation typically had the lowest activation (Figure 4A). Single and dual vectors altered activation in nine muscles during abduction, and six muscles during flexion (Figure 4B). Main effects of exercise affected the biceps, flexor digitorum, extensor digitorum and serratus anterior ($p<0.001$). Mean activation in the biceps and serratus anterior was higher during the abduction and flexion exercises than the internal or external rotation exercises, but these two exercises were not significantly different from one another. Mean activation in the flexor digitorum during the internal rotation exercise (11.83 ± 2.88 %MVC) were higher than the external rotation or flexion trials (9.37 and 9.38 %MVC, respectively), but no other exercises were different from one another. Mean activation in the forearm extensors were highest in the internal rotation exercise (16.1 ± 3.17 %MVC) were higher than the flexion trial (11.29 %MVC), but no other post-hoc differences between exercises were present. Main effects of single/dual vector exercises were present in the flexor digitorum and extensor digitorum ($p<0.001$); in both muscles, activation was higher in the dual vector exercise.

PEAK ACTIVATION

Interactions between exercise and single/dual vector affected peak EMG for some muscles; those with no interaction had significant main effects of exercise. Interactions were present in the middle and posterior deltoid, supraspinatus, infraspinatus, and upper, middle and lower
trapezius (p = 0.0005-0.0437) (Table 2). The dual vector abduction exercise had the highest activation for all of these exercises except for the infraspinatus, with the highest activation during the dual vector external rotation exercise (86.62 ± 6.32 %MVC). Within an exercise, moving from single to dual vectors increased activation in abduction for six muscles (Figure 5). Main effects of exercise were observed in the anterior deltoid, sternum and clavicular heads of pectoralis major, serratus anterior, biceps, triceps, latissimus dorsi, and extensor digitorum (p<0.001-0.004). Across all of these muscles, the peak EMG in internal rotation was significantly lower than other exercises and significantly higher in flexion or abduction except for extensor digitorum, where internal rotation (40.46 ± 10.16 %MVC) was significantly greater than flexion (24.68 ± 7.96%MVC), but no other exercises were different from one another (Figure 5A).

A main effect of single/dual vector affected peak EMG in the middle deltoid (p = 0.0088) and latissimus dorsi (p = 0.0524); use of a dual vector increased peak EMG in both of these muscles from 48.07 to 52.78 ± 4.23 %MVC and 30.53 to 35.21 ± 6.46 % in middle deltoid and latissimus dorsi, respectively (Figure 5B). No significant changes were present for flexor digitorum.

**INTEGRATED EMG**

Interactions between exercise and single/dual vectors influenced iEMG for most muscles; all other muscles were affected by main effects of exercise selection or number of resistance vectors. Interactions affected integrated EMG of the anterior, middle and posterior deltoid, sternum and clavicular heads of pectoralis major, triceps, latissimus dorsi, supraspinatus, infraspinatus, and upper, middle and lower trapezius (p <0.001-0.0198) (Table 3). All of these muscles except for anterior deltoid, the clavicular head of pectoralis major and latissimus dorsi had the highest integrated EMG in the dual vector condition during abduction. Peak integrated EMG in the anterior deltoid and clavicular head of pectoralis major was highest in the single vector flexion exercise (275145.2 ± 17799.8 and 102106.6 ± 7336.0 %MVC*s, respectively). Latissimus dorsi integrated activation was highest in the dual vector condition during flexion (182728.0 ± 22557.8 %MVC*s). Main effects of exercise were present in serratus anterior, biceps, flexor digitorum and extensor digitorum (p<0.001-0.395). In serratus anterior and biceps, the abduction and flexion conditions increased integrated activation compared to internal or external rotation by up to 163% and 162 % respectively, but no other differences were present. The internal rotation condition generated 42% higher integrated activation compared to the flexion condition in extensor digitorum and 27% higher than flexion or external rotation conditions in flexor digitorum, but no other differences were present.

**DISCUSSION**

The purpose of this study was to investigate differences in muscle activation between dual vector and traditional single vector resistance exercises. The location and direction of the secondary vector in the abduction and flexion exercises created a resistance beyond the primary vector. In the internal and external rotation conditions, the secondary vector resisted horizontal adduction and abduction, respectively. The hypothesis of this work was that the dual vector exercise would increase muscle activation was partially supported, with increased activation for some muscles in the abduction and flexion dual vector exercises, but minimal changes existed when adding a dual vector to the internal or external rotation tasks, indicating that adding a dual vector was not universally beneficial.

Although the abduction and flexion dual vector exercises were effective at increasing global activation, the abduction task increased activity in a greater number of muscles; changing to dual vector exercises with internal or external rotation appeared to result in only marginal changes to muscle activation. The dual vector exercise condition for abduction increased mean activation in nine muscles, peak activation in six muscles and iEMG in nine muscles, while the dual vector flexion exercise increased mean activation in six muscles, no muscles in peak activation, and three muscles in iEMG. Horizontal abduction and elevation in the frontal plane has been demonstrated to target the upper and lower trapezius more than flexion exercises. In the abduction task, the primary vector provided resistance to elevation in the frontal plane, while the dual vector resisted horizontal abduction. As both of these movements target the trapezius, this may explain differences between the
flexion and abduction tasks. As the posterior deltoid is a horizontal abductor at the shoulder, changes in activity were expected with the addition of the dual vector; however, changes were only observed in the abduction and external rotation conditions. Maximum EMG activity is expected from the posterior deltoid during horizontal abduction at 90° abduction.\textsuperscript{35} A similar posture was adopted during the abduction and external rotation dual vector conditions. Supraspinatus activity only increased in the abduction dual vector condition; the supraspinatus operates as a shoulder abductor and glenohumeral stabilizer and is expected to have greatest activity in abduction or horizontal abduction.\textsuperscript{36,37} Adding a second vector to internal or external rotation tasks did not appear to alter muscle activation across the muscles examined. The dual vector exercises only significantly increased muscle activation in the mean and iEMG values for the clavicular head of pectoralis major in internal rotation and the posterior deltoid in external rotation. In both of these cases, the difference in mean activation was less than 4.1 %MVC. While these increases in activation may be statistically significant, the small absolute difference may not identify these changes as clinically meaningful.\textsuperscript{38,39}

Shoulder rehabilitation exercises are designed to isolate specific muscles while remaining cognizant of potential subacromial space changes. During active arm elevation, particularly in flexion and abduction, the rotator cuff and scapular muscles play an important role in maintaining the subacromial space.\textsuperscript{40–43} With the addition of the dual vector in abduction, increased activity was seen in the middle and posterior deltoids. This would likely joint compression at 90° of abduction, as this compressive force is centralized in the glenoid fossa.\textsuperscript{37} Increasing co-contraction of adductor muscles has been demonstrated to reduce patient complaints and pain scores in individuals with subacromial pain syndrome;\textsuperscript{44} increasing activation in rehabilitation could lead to beneficial outcomes in the future. Exercises or movements that protect against SLAP lesions are ones that activate biceps, triceps, latissimus dorsi and upper trapezius;\textsuperscript{45} adding a second vector increased mean activation in triceps, latissimus dorsi and upper trapezius, which may be beneficial for shoulder health. If the goal of dual vector exercises is to increase global activation, this method of exercise may be suitable for use towards the end of a rehabilitation program as a progression of traditional resistance band exercises. Recent research has incorporated this dual vector rehabilitation strategy for overhead athletes\textsuperscript{46} in an attempt to modulate lower trapezius activation, and found increased activation when using a dual vector strategy compared to a single vector. As the lower trapezius maintains scapular position during the late cocking phase of throwing,\textsuperscript{47} it is plausible that this dual vector strategy would alleviate lower trapezius activation, which is associated with scapular dyskinesis and SLAP lesions in baseball pitchers.\textsuperscript{48} This work observed increased mean, peak and integrated lower trapezius activation in dual vector exercises, supporting these findings.

Some inherent limitations are present in this work. The population studied was limited to healthy university aged males who had no shoulder or arm pain in the prior 12 months, limiting its potential utility for older or pathologic populations. Only four exercises were investigated, however many shoulder exercises using elastic resistance bands exist for different shoulder rehabilitation purposes. The exercises selected are commonly used and represent a range of elastic resistance postures. The second vector was held in the hand for abduction and flexion, versus being attached at the elbow for internal and external rotation. This might have caused the resistance arm of the dual vector to be smaller, potentially decreasing the second vector’s load at the shoulder. The concentric and eccentric phases were not divided within a repetition for dependent variable calculation; as such, it is difficult to comment on timing of these activations. Future research should differentiate between concentric and eccentric phases of these motions to expand on these findings. RPE was not collected during experimental trials; while participants were instructed to select a band that would allow for 12-15 continuous repetitions, there may be variations in intensity across participants. Due to varying resistance arm lengths with different band attachment locations, variable band tensions should be investigated further, as this study was done with low resistance. However, band lengths were normalized to 125% stretch at the peak of each repetition in each exercise.

**Figure 5:** A) An interaction between exercise and number of elastic vectors affected peak activation in supraspinatus, with increased activation in the dual vector abduction task. Significant differences in this interaction are denoted by letters; data points not sharing a letter are significantly different. B) Changing between single and dual vectors in flexion altered activation in eight muscles; differences between single and dual vector activation is indicated by asterisks.
Table 1: Exercise * Single/Dual vector interactions for normalized mean muscle activity (%MVC).

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Note: Muscles with significant interactions have their rows highlighted grey; post-hoc differences within that muscle are denoted by letters within data cells; values in a row not sharing a letter are significantly different from one another.

ADEL = Anterior deltoid; MDEL = Middle deltoid; PDEL = Posterior deltoid; PECS = Pectoralis major (sternal head); PECC = Pectoralis major (clavicular head); SERR = Serratus anterior; BICP = Biceps; TRIC = Triceps; LATS = Latissimus dorsi; FDS = Flexor digitorum superficialis; ED = Extensor digitorum; SUPR = Supraspinatus; INFR = Infraspinatus; UTRP = Upper trapezius; MTRP = Middle trapezius; LTRP = Lower trapezius
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</table>

Note: Muscles with significant interactions have their rows highlighted grey; post-hoc differences within that muscle are denoted by letters within data cells; values in a row not sharing a letter are significantly different from one another.

ADEL = Anterior deltoid; MDEL = Middle deltoid; PDEL = Posterior deltoid; PECS = Pectoralis major (sternal head); PECC = Pectoralis major (clavicular head); SERR = Serratus anterior; BICP = Biceps; TRIC = Triceps; LATS = Latissimus dorsi; FDS = Flexor digitorum superficialis; ED = Extensor digitorum; SUPR = Supraspinatus; INFR = Infraspinatus; UTRP = Upper trapezius; MTRP = Middle trapezius; LTRP = Lower trapezius.
CONCLUSION

The results of this study demonstrated differences in muscular activation when changing between single or dual vector elastic resistance and exercise selection. While dual vector exercises typically elevated muscular activation, statistical increases within an exercise existed primarily in abduction and flexion. Due to the increased activity in the scapular stabilizers, shoulder extensors, and horizontal abductors, these exercises may be suitable for individuals rehabilitating a shoulder injury. While improving shoulder muscle activation in flexion and abduction, the addition of the dual vector could allow for greater impacts in the trapezius that are not seen with a single vector. Adding a second vector to our internal or external rotation exercise appeared to provide minimal muscle activity changes.

These findings can be leveraged in upper extremity rehabilitation programs to increase activation in the upper extremity but use of a dual vector is not universally beneficial across exercises. Consideration of the rehabilitation plan, targeted muscles and exercises of interest are needed, as dual vector exercises may not be universally beneficial.

CONFLICT OF INTEREST STATEMENT

None of the authors have any conflict of interest related to the equipment, methods or results used in this work.

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Concurrent Validation and Reference Values of Gluteus Medius Clinical Test

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Context
The hip abductor muscles, mainly the gluteus medius, are responsible for controlling hip adduction in a closed kinetic chain. Frontal plane knee alignment, assessed during functional activities such as squatting, jumping and running, may overload joint structures, like the anterior cruciate ligament and patellofemoral joint. The hand-held dynamometer is reliable and effective for testing the muscular strength of the hip abductors.

Objectives
(1) To assess the concurrent validity between the gluteus medius clinical test and a maximum isometric force test of the hip abductors using the hand-held dynamometer; (2) to determine the intra and inter-examiner reliability for the application of the gluteus medius clinical test; and (3) to describe reference values of gluteus medius clinical test on a population of youth athletes.

Design
Cross-sectional.

Methods
Thirty healthy individuals were recruited for validity and reliability testing. On the first day, participants performed the maximal isometric test of the hip abductors, measured via hand-held dynamometry. On the following week, the gluteus medius clinical test was performed. Intraclass correlation coefficients (ICC\(_{2,2}\)) were computed for the reliability analysis, with a 95% confidence interval. To generate reference values, the gluteus medius clinical test was performed on 273 athletes.

Results
The results of this study indicated a weak positive correlation (r = 0.436, p = 0.001) between tests, which indicates that they examine different domains of gluteus medius muscle function, likely endurance and muscle strength. The magnitude of computed ICCs (>0.95) indicates excellent intra- and inter-examiner reliability.

Conclusion
The findings of the current study indicate that the gluteus medius clinical test is reliable and examines a domain of muscular function not fully captured by HHD. The clinical test developed in this study is low-cost and can be included for gluteus medius assessment.

Level of evidence
Level 3.
INTRODUCTION

The hip abductor muscles, mainly the gluteus medius (GM), are responsible for controlling hip adduction in closed kinetic chain, and are associated with preventing dynamic knee valgus during the single leg squat. Dynamic knee valgus can result in injuries, such as anterior cruciate ligament (ACL) tears and patellofemoral joint pain (PFJP). Diminished GM volume has been found in individuals with PFJP compared to control participants. The primary hip abductors are the GM, the gluteus maximus and the tensor of the fascia lata. The gluteus medius is the largest abductor, representing approximately 60% of the transverse area of this muscle group. In addition, the posterior GM fibers also produce lateral hip rotation, which helps to reduce excessive medial rotation and influence dynamic knee valgus in an attempt to maintain dynamic hip stability during functional activities. Studies have shown that maintaining pelvic stabilization and good knee kinematics require adequate GM action.

Muscle fatigue is important factor to consider during squatting and jumping. Fatigue may be associated with lower limb misalignment, especially in long-duration sports, such as running. Geiser et al. showed that hip abductor fatigue increases the dynamic valgus during jumps, which may increase risk of knee injuries. Therefore, good muscular function of the GM is necessary, considering both strength and endurance.

Objective information about muscular strength is clinically relevant because it supports formulation of treatment plan and selection of preventive interventions. One of the devices used to measure muscle strength is the hand-held dynamometer, which has concurrent validity with the isokinetic dynamometer, considered the gold standard. According to Jaramillo et al., the hand-held dynamometer is a reliable tool for testing hip abductor strength. However, the practicality and utility of this tool has been questioned due to cost (~$1,000.00 USD) and the requirement for yearly calibration. Additionally, a recent meta-analysis describing risk factors for patellofemoral pain has shown limited evidence related to hip strength measured using the hand-held dynamometer. Neal et al argued that isometric muscle testing may not be sensitive enough to identify individuals at risk of PFJP. Considering these limitations of the hand-held dynamometer and the requirement to quantify GM muscle function in clinical practice, the purposes of the present study were: (1) to perform concurrent validation of the GM Clinical Test with the isometric torque test using the hand-held dynamometer; (2) to determine the intra and inter-examiner reliability of GM Clinical Test; and (3) to describe reference values of GM Clinical Test in a population of youth athletes.

METHODS

STUDY DESIGN

The present study was a cross-sectional study to determine concurrent validation, reliability, and reference values for the GM clinical test.

PARTICIPANTS

For examination of concurrent validity and reliability, 30 participants (15 men and 17 women) were selected. The mean age was 36.4 years (±16.6), and body mass was 70.43 kg (±15.02). The inclusion criteria were: (a) absence of pain or history of injury in lower limbs; (b) no history of surgery in the lower limbs in the prior six months. Participants who reported pain during the application of the tests were excluded from this study.

For reference values, 273 athletes (81 women and 192 men) from a sports club were selected during the pre-season assessment with a mean age of 14.6 years (±2.1), height 1.75 m (±1.4), and body mass of 65.1 kg (±15.7). The athletes were part of the volleyball, basketball and judo teams. The same examiners from the reliability study performed the clinical gluteal endurance test on athletes to ensure the required standardization for reference values.

PROCEDURES

The present study was approved by the Ethical Committee of the Universidade Federal de Minas Gerais (ETIC No. 493/2009) and all individuals who agreed to participate in the study signed the informed consent. The participants were personally invited by researchers and through social media to participate in the present study.

The hip abductor isometric torque was measured using a hand-held dynamometer (microFET2, Hoggan Health Industries, Inc., West Jordan, UT), considered a valid and reliable instrument for measuring muscle strength. The subject was positioned in the side lying position with the upper limbs crossed in front of the trunk, aligned scapular and pelvic girdles, the hip and knee of the contralateral lower limb to the limb tested were flexed, and the tested lower limb was positioned with the hip in neutral in the sagittal plane and the knee extended (Figure 1). The hand-held dynamometer was positioned 5 cm above the knee joint inter-line, and attached to a Velcro® strap that allowed hip abduction in the frontal plane.

The subject was asked to perform hip abduction until the movement was restricted by Velcro®, and maintained max-
imal isometric contraction for five seconds with standardized verbal command. This procedure was performed three times in each lower limb, with a 15 second interval between measurements. The abductor torque was calculated by the average of three values measured, multiplied by a measurement of the distance between the greater trochanter of the femur to 5 cm above the lateral knee joint line. The torque value was divided by body mass to obtain normalized data (Nm/kg). Intra- and inter-examiner reliability analysis was performed on 30 participants, with a seven-day interval between the assessments.

The GM Clinical Test was performed in the same position as the torque test. The individual was in the side lying position with the upper limbs crossed in front of the trunk, aligned scapular and pelvic girdles, flexed contralateral hip and knee, and the limb being tested with an extended hip and knee (Figure 2). Widler et al. reported that this position is the most valid and reliable for hip abductor strength evaluation, verified by the GM electromyographic activity. The abduction movement of the evaluated lower limb was performed without any external resistance.

The individual was asked to perform the hip abduction movement maintaining the initial position, and the number of repetitions was not previously suggested to the participants, although it was standardized to a maximum of 15 repetitions. The range of motion was not previously informed either, but the examiners asked the participants to avoid changing the initial position of pelvis and trunk. The time to accomplish this test was not controlled. The examiner registered the number of repetitions corresponding to the test interruption. The test was interrupted by verbal command at repetition 15 when the participant did not perform any compensation.

STATISTICAL ANALYSES

Mean and standard deviation for the dominant and non-dominant limbs was computed to normalize the primary study variables: body-mass normalized abductor torque and number of repetitions of GM Clinical Test. Concurrent validity between tests was examined using Pearson correlation coefficient and simple linear regression to obtain the coefficient of determination ($r^2$). To determine GM Clinical Test intra- and inter-reliability, $ICC_{2,2}$ with a 95% confidence interval was used.

RESULTS

CONCURRENT VALIDATION AND RELIABILITY STUDY

The values obtained for the concurrent validity and reliability analysis were from both limbs from the 30 participants. The mean normalized torque value of the hip abductors measured by HHD was 1.2 (±0.39) Nm/kg, and the mean number of repetitions in the GM Clinical Test was 5.7 (±4.06) repetitions.

A significant weak correlation was observed between the hand-held dynamometer test for hip abductor torque and the GM Clinical Test ($r = 0.456; p = 0.001$). Simple linear regression demonstrated a low coefficient of determination ($r^2 = 0.19$), which means that 19% of the hip abductor isometric torque variation is explained by the number of the clinical test repetitions. The intra-examiner reliability for the GM Clinical Test was high (Examiner 1=0.98; Examiner 2=0.96), and the inter-rater reliability for the GM Clinical Test was also considered high (0.95) (Table 1).

REFERENCE VALUES STUDY

For the 273 youth athletes, the mean values found in the GM Clinical Test were 4.1 (± 3.9) repetitions on the dominant limb (D) and 3.4 (± 3.1) repetitions on the non-dominant limb (ND). In female athletes, the mean number of repetitions on the D limb was 4.1 (± 4.9) and on the ND 3.4 (± 5.5). In the male athletes, the mean number of repetitions on the D side was 3.6 (± 5.0) and on the ND 2.9 (± 3.1). The mean values in relation to sport participation are presented in Table 2.
athletes. The results indicated a significant, but weak correlation between GM Clinical Test and hand-held dynamometer test ($r = 0.456$ and $r^2 = 0.19$). The reference values for clinical test were $4.1 (±3.9)$ repetitions on the D limb and $3.4 (±3.1)$ repetitions on the ND limb on average. The ICC values found in this study, above 0.95, are indicative of excellent intra- and inter-examiner reliability. These findings allow physiotherapists to reproduce both of these testing methods in clinical practice, in order to quantitatively evaluate the strength and possibly muscular endurance of hip abductors.

The hand-held dynamometer is a valid and reliable tool used to quantify muscular strength, and is considered a practical instrument, due to its portability and size, compared to the gold standard, the isokinetic dynamometer. The hand-held dynamometer test for hip abductor strength is performed through maximum isometric contraction, where the muscle force corresponds to its maximum capacity to generate tension. In general, tests that use the HHD are less used in practice for prescription of exercises, due to the high cost of the instruments and difficulty of operation. Additionally, the majority of sports activities are dynamic in nature and isometric strength may not be the best way to assess muscle function in this context.

On the other hand, the GM Clinical Test represents the ability to perform muscle contractions under submaximal loads. The muscular action tested by the two methods is likely different, testing two domains, strength and endurance. Both domains are important to prevent musculoskeletal injuries, to exercises prescription and to promote joint stability. Moreover, a recent study was designed to assess hamstring endurance in soccer athletes through the unilateral hip bridge test. As with the present study, the repetitions were interrupted if there was a change in movement pattern and performing less than 22 repetitions was associated with hamstring strain. Therefore, the GM Clinical Test could be used complementary to the hand-held dynamometer or when it is not possible to purchase a HHD in low-income sports context.

The hip abductor isometric torque and the GM Clinical Test were significantly correlated, although only at $r = 0.456$. According to Portney et al., values between $r = 0.25$ and $r = 0.50$ represent a weak correlation. Correlation coefficients between clinical measures ranging from 0.57 to 0.78 are considered appropriate values for clinical practice, meaning that these tests cannot be used interchangeably. However, the isometric hip abductor test and the GM Clinical Test showed high values of intra-examiner reliability (Table 1), since values above 0.90 are indicative of excellent reliability. These findings demonstrate that both tests can be reliably replicated in clinical practice for physical therapy evaluation and re-evaluation of the different strength and endurance domains of the hip abductors.

Muscle endurance also is important to preserve joint stability during sports movement. When a muscle fatigues, there is overload in the passive elements, such as capsules and ligaments, as well as movement pattern changes. Fatigue may be associated with injury risk, because its influences the lower limbs’ alignment. For example, muscle endurance deficits may be an important contributing factor in the development of PFJS. Van Cant et al demonstrated an important endurance deficit of hip abductor muscles in patients diagnosed with PFJS. Recent authors have demonstrated a correlation between low endurance of GM and excessive dynamic valgus, and it is known that fatigue may predispose athletes to knee injuries due to changes in alignment and dynamic knee joint stability. Lower limb injuries, such as ACL rupture during landing from an uncontrolled jump, often occur during the last 15 minutes of the first half and in the last 30 minutes of the second half in a football match. Additionally, the American College of Sports Medicine recommends that endurance must be included in a training program, as well as muscle strength exercises. Considering the influence of fatigue on sports injuries, practitioners involved in prevention and rehabilitation of musculoskeletal injuries should consider a periodic assessment of muscle endurance in order to protect the athlete in sport settings.

The reference data from the present study demonstrated that youth athletes participating in volleyball, basketball and judo, on average, can perform four repetitions of hip abduction without movement compensation. Until now, studies using the same methodology are not available. Therefore, the authors cannot compare the present data for youth athletes with other studies. However, a study by Freckleton et al evaluated hamstring endurance in young soccer athletes through the unilateral bridge test, and the athletes with a previous history of hamstring strain performed on average, 22 repetitions, while the uninjured athletes did 26 repetitions. Despite being different tests, the

Table 2: Reference values of the GM Clinical Test (in number of repetitions). Data are presented as means (SD).

<table>
<thead>
<tr>
<th></th>
<th>Volleyball</th>
<th>Basketball</th>
<th>Judo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dominant Side</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean (± SD)</strong></td>
<td>4.2 (± 3.5)</td>
<td>3.6 (± 4.1)</td>
<td>4.8 (± 4.7)</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>15</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td><strong>Non-dominant Side</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean (± SD)</strong></td>
<td>3.6 (± 2.8)</td>
<td>2.6 (± 2.9)</td>
<td>4.5 (± 3.8)</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>13</td>
<td>13</td>
<td>15</td>
</tr>
</tbody>
</table>
parameter of muscular endurance was evaluated in the two studies and the results of the present study demonstrate that athletes are likely to have low GM endurance.

Some limitations of the study should be considered. The hand-held dynamometer test involves all the abductor muscles of the hip, GM, gluteus minimus, tensor fascia lata, and sartorius, as demonstrated by Widler et al.\textsuperscript{13} in an electromyographic study. In contrast, during the GM Clinical Test, the evaluation of the GM was prioritized, by maintaining the hip extension position of the lower limb tested. Therefore, the clinical test developed in the present study provides complementary information to that from the hand-held dynamometer test, and the clinical test developed by this study may be a useful tool to evaluate GM function.

CONCLUSIONS

The present study demonstrated that the GM Clinical Test has a weak correlation with the isometric hip abductor torque test using a hand-held dynamometer. Both testing methods were reliable and repeatable between and within examiners. In addition, reference values were obtained for youth athletes. The clinical test developed in this study is a reliable, useful and low-cost method that can be included in evaluation and re-evaluation of the GM.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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REFERENCES


Original Research

Hip Abduction Strength: Relationship to Trunk and Lower Extremity Motion During A Single-Leg Step-Down Task in Professional Baseball Players

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Background
The single-leg step down task (SLSD) is a clinical tool to assess movement and control of the lower extremity and trunk. Hip abduction weakness may impact movement quality during the SLSD, however the relationships between movement and strength are unclear.

Purpose
To determine the relationship between hip abduction isometric strength and movement during the SLSD of trunk lean, pelvic drop, knee valgus, and hip flexion.

Study Design
Cross sectional, cohort study

Methods
One hundred-eighteen Minor League baseball players (age=21.6 ± 2.0 years; n=68 pitchers, n=50 position players) participated. Bilateral hip abduction isometric strength was measured using a handheld dynamometer (HHD), and then multiplied by distance from the greater trochanter to the HHD and expressed as hip abduction torque. Video cameras captured the SLSD, with participants standing on one leg while lowering their contralateral heel to touchdown on the floor from a 0.203m (8in.) step. Trunk lean, trunk flexion, pelvic drop, knee valgus, and hip flexion were measured using Dartfish at heel touchdown. A value of 180° indicated no knee valgus. Pearson correlations examined the relationships between hip abduction torque and SLSD motions.

Results
There were no significant correlations for position players. For pitchers, on the lead leg increased hip abduction torque weakly correlated with a decrease in knee valgus (r= 0.24, p=0.049). Also for pitchers on the trail leg, increased hip abduction torque weakly correlated with decreased pelvic drop (r= -0.28, p=0.021).

Conclusion
Hip abduction strength contributes to dynamic control of the trunk and legs. Specifically in pitchers, hip abduction weakness was related to increased movement of the lower extremity and lumbopelvic regions during the dynamic SLSD task. These deficits could translate to altered pitching performance and injury.

Levels of Evidence
2.

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INTRODUCTION

The lower extremities and trunk are critical components for power generation during throwing or hitting sports. When throwing a baseball, force is initiated by the legs, transferred to the trunk and then to the upper extremity for ball release. The proximal segments of the hip and trunk are estimated to contribute 50% of the kinetic energy and force during dynamic overhead arm activities. Any alterations in proximal segmental sequencing or force transfer can alter the kinetics and kinematics at the distal joints, leading to increased joint and soft tissue stress. Disruptions in the kinetic chain can increase forces at the shoulder and elbow, and these increased forces have been associated with arm injuries in baseball players.

The hip abductor muscle group has a direct effect on motion at the hip via their proximal and distal attachment sites. They also have an indirect effect on motion at the trunk via the attachment of the gluteus maximus to the pelvis and lumbar spine, via the thoracolumbar fascia. During a dynamic single-leg landing task, individuals with hip abductor and extensor weakness had increased trunk lean towards the stance limb. Moreover, greater trunk lean occurred in participants with hip weakness despite increased activation of the trunk musculature. The hip abductor muscle group also has a direct influence on both lower extremities during throwing. On the trail leg (ipsilateral to the throwing arm) the abductors function to stabilize the pelvis and provide balance during the wind-up and early cocking phases. The lead leg (contralateral to the throwing arm) functions to decelerate the knee, provide a stable base, and absorb the force transferred from the deceleration and follow through phases. Hip abductors that exhibit high activity during pitching include the gluteus maximus and medius. The gluteus maximus is more active on the trail leg, while the gluteus medius is more active on the lead leg. Moreover, lead leg gluteus medius activity was inversely related to the rate of axial pelvis rotation during arm-cocking phase, as well as directly related to the rate of axial pelvis rotation at maximal external rotation, indicating a two-fold role of the gluteus medius, serving as a pelvic stabilizer and controlling the rate of axial pelvis rotation. Based on their action, weak hip abductors may cause compensatory dynamic knee valgus or pelvic drop leading to further movement compensations up the kinetic chain distally at the shoulder and elbow.

Single-leg dynamic tasks such as a squat, step-down, or stance are functional tests that can be used to assess trunk and lower extremity control. The lumbopelvic motion deficiencies seen during these single-leg dynamic tasks are related to altered pitching mechanics, performance, and incidence of arm injuries. The single-leg squat can detect lateral trunk lean deficits and predict the amount of trunk lean observed during pitching. The single-leg stance test has identified deficits in lumbo pelvic control that are related to poor pitching performance and injury risk, and to increased shoulder horizontal torque and elbow varus torque during pitching. Movement deficits during single-leg dynamic tasks have implications for pitching, but it is unclear what factors contribute to these deficits. Moreover, movement deficits during dynamic tasks could theoretically also impact position player performance and injury risk; there is lack of evidence supporting this hypothesis.

The purpose of this study was to determine the relationship between hip abduction isometric strength and trunk lean, trunk flexion, knee valgus, pelvis drop, and hip flexion motions during a single-leg step down task (SLSD). It was hypothesized that hip abduction strength would be negatively correlated to the degree of motion deficits. Identifying the relationship of hip abduction strength to kinematics during a dynamic task will provide a foundation to understand why these motion deficits occur and enable the development of programs that minimize and prevent upper extremity injuries in baseball players.

METHODS

PARTICIPANTS

Data were collected for this prospective study as part of 2017 pre-season physical examinations on Minor League baseball players from a single organization. Participants were required to meet the following inclusion criteria: 1) free from injury at the time of testing, and 2) on a team roster in the participating organization for the full competitive season. The duration of time that the players were free from injury was not accounted for. Participants were excluded if any of the following criteria were met: 1) not cleared to participate in baseball activities, 2) currently receiving treatment for an injury, and 3) players not on a team roster with the participating organization for the full competitive season. Pre-season strength and conditioning program records were not available. Individualized strength and conditioning programs were performed during the season but the details were not available for analysis. This study was approved by the University of Southern California Institutional Review Board and all participants provided written informed consent.

PROCEDURES

Pre-season assessments were performed at the organization's Minor League training facility. A health questionnaire regarding current upper extremity injury status and upper extremity injury history for the past year was completed by all participants. Specific injury questions included body part injured, injury diagnosis, time lost due to the injury, and upper extremity surgical history. Each participant’s health history was reviewed by a member of the organization’s sports medicine staff to ensure accuracy. Demographic data such as age, height, weight, position, throwing arm, and years of Minor League Baseball participation were also collected. Participants next underwent testing for the SLSD and hip strength on both the lead and trail legs. The lead leg (stride leg) is defined as the leg contralateral to the throwing arm and the trail leg (stance leg) is ipsilateral to the throwing arm.

Hip abduction isometric strength was assessed with the participant in a side-lying position with the hip placed in approximately 20 degrees of abduction, legs fully extended in line with the trunk, and supported with a pillow between the knees (Figure 1). A strap placed just proximal to the...
iliac crest and secured to the table was used to stabilize the trunk. A hand-held dynamometer (HHD) (MicroFet 2, Hoggan Scientific, West Jordan, UT, USA) was placed 5 cm proximal to the lateral knee joint line and stabilized with a strap. Participants performed two maximal effort isometric contractions trials held for five seconds, with verbal encouragement given throughout each trial to help ensure maximal effort. Hip strength testing was performed as a "make" test, with participants meeting the resistance applied by the strap. Motion was visually monitored to ensure the participants did not attempt to compensate at the trunk or hip in the sagittal plane (flexion/extension) or transverse (rotation). Leg length was recorded as the distance from the greater trochanter to the placement of the HHD. Hip abduction torque (Nm) was calculated by multiplying the HHD value by the leg length (m). Two trials were averaged for each leg, and used for data analysis. Test-retest reliability for hip abduction isometric strength was established in a prior pilot examination (n=7), and Interclass Correlation Coefficient (ICC 3,2) was 0.96, with a standard error of the measure (SEM) of 18.9 N and a minimal detectable change (MDC90) of 44.2 N.

The single-leg step-down (SLSD) task was performed twice on both the trail and lead legs. Reflective markers (n=9; 14.0 mm) were attached on the sternum, bilateral greater trochanter, bilateral anterior superior iliac spine (ASIS), bilateral fibular head, and bilateral lateral malleoli using double-sided tape. Participants stood on a single leg, on a 0.203 m (8 in) step, and lowered their contralateral heel to the ground over two seconds. Once the heel touched the ground, they returned to the starting position over two seconds, controlled with verbally counting 'one-one thousand, two-one thousand'. Video cameras were mounted on tripods and placed 3.56 m from the box in the frontal and sagittal planes (Sony Handycam CX405 HDR, New York City, NY, USA).

Dartfish software (Dartfish USA Inc., Alpharetta, GA, USA) was used to measure 2D hip flexion, knee valgus, trunk flexion, trunk lateral lean, and pelvic drop angles (Figure 2). Prior to analysis, the videos from the frontal and sagittal planes were synced, and the point of joint angle measurements were taken during the SLSD when the contralateral heel first touched the ground. Hip flexion in the sagittal view was defined as the angle between the horizontal global axis, and the line between the fibular head marker and the greater trochanter marker. Knee valgus angle in the frontal plane was defined as the frontal plane projection angle, by a line between the ASIS marker to the center of the patella, and a second line from the patella to the midpoint of the talocrural joint. A value of 180° indicated no knee valgus. Trunk flexion angle in the sagittal view was defined as the angle between the vertical global axis and the line between the fibular head marker and the greater trochanter marker. Knee valgus angle in the frontal plane was defined as the frontal plane projection angle, by a line between the ASIS marker to the center of the patella, and a second line from the patella to the midpoint of the talocrural joint. A value of 180° indicated no knee valgus. Trunk flexion angle in the sagittal view was defined as the angle between the vertical global axis and the line between the greater trochanter marker that bisects the trunk segment. Trunk lateral lean angle was defined as the vertical global axis and a second line at the midpoint of the two ASIS markers extending to the sternal notch marker. Absolute trunk lean was assessed therefore the direction of lean was not considered, only the magnitude of lean either towards or away from the stance leg. Pelvic drop was measured in the frontal plane and was defined by the horizontal global axis beginning at the ASIS marker on the weight bearing leg and a second line extending to the ASIS marker on the non-weight bearing leg. Each variable was assessed for the two SLSD trials and the average was calculated for data analysis. Test-retest reliability for all SLSD joint angles

Figure 1: Hip abduction isometric strength of the top leg, with the hand-held dynamometer between the belt and leg.

Figure 2: Single-leg step down joint angles. A. hip flexion, B. knee valgus via the frontal plane projection angle, C. pelvic drop D. trunk flexion E. trunk lateral lean
was established prior to data analysis (n=10). The ICC 3,2 and standard error of the mean (SEM) for lower extremity kinematics during the SLSD were: hip flexion 0.9 (4.9°) with an MDC95 of 15.6° and knee valgus via the frontal plane projection angle 1.0 (1.3°) with an MDC95 of 3.6°. The ICC 3,2 and (SEM) for trunk flexion was 1.0 (1.0°) with an MDC95 of 2.9°. Trunk lateral lean angle had an ICC 3,2 and (SEM) of 1.0 (0.8°) with an MDC95 of 2.2°. The ICC 3,2 and (SEM) for pelvic drop was 1.0 (1.0°) with an MDC95 of 2.7°.

### STATISTICAL ANALYSIS

Descriptive statistics were calculated for all demographic variables. Pearson product moment correlation coefficient analyses were performed to determine the relationship between hip abduction torque and motion variables of trunk lean, trunk flexion, hip flexion, knee valgus via the frontal plane projection angle, and pelvic drop during the SLSD. Separate analyses were performed for position players and pitchers for both the lead and trail legs. Statistical significance was set a priori at p < 0.05 and all analyses were performed using IBM SPSS Statistics Version 24.0 software (International Business Machines Corp., Armonk, NY, USA).

### RESULTS

One-hundred and thirty Minor League baseball players participated, but 12 players did not complete all measures and were removed from the data set (Table 1), leaving 118 for data analysis. All measures and correlations between hip abduction torque and SLSD joint angles data are presented in Table 2. For position players (n=50), there were no significant correlations between hip abduction torque and SLSD variables. For pitchers (n=68) on the lead leg, decreased hip abduction torque was associated with increased knee valgus (r= 0.24, p=0.049). In the trail leg of pitchers, decreased hip abduction torque was associated with increased pelvic drop (r = -0.28, p=0.021).

### DISCUSSION

Overall, the gluteal musculature needs to function as a whole in order to stabilize the pelvis and control the femur during dynamic tasks. However, it is unclear what factors, specifically, contribute to observed movement deficits during single-leg dynamic tasks. Both the gluteus maximus and gluteus medius have been found to be important stabilizers of the pelvis in pitchers. The hip abductors, along with other musculature about the hip and pelvis, are associated with control of the pelvis and femur during the SLSD in pitchers. Specifically, hip abduction strength was found to be negatively correlated to frontal plane deviations of greater pelvic drop on the trail/stance leg and knee valgus on the lead/stride leg. In other words, there was greater knee valgus and pelvic drop with lower values of hip abduction strength, but only in pitchers. Although significant, the results demonstrate a weak relationship for which the clinical significance is unknown. This likely indicates that the abductors are only one contributor to the observed changes in knee valgus and pelvic drop. The strength of other muscles that contribute to lower extremity kinematics during the SLSD were not assessed. The movement deviations seen during the dynamic SLSD task related to hip abduction strength deficits may reveal compensations that affect pitching performance. If the deviations in pelvic drop and knee valgus are mirrored during throwing due to hip abductor weakness, there may be negative effects on the transmission of forces distally. This is only a postulate, as kinematics during pitching were not assessed in this study. The SLSD task detected deficits in dynamic control of the pelvis and lower limb. There may be potential value of the SLSD test to determine movement control and hip abduction strength deficiencies in baseball players, particularly in pitchers.

Knee valgus has been related to lower extremity injury risk during dynamic movement tasks. Specifically, female athletes with greater knee valgus during a jump landing task had a greater rate of a subsequent anterior cruciate ligament injury. Moreover, athletes sustaining a non-contact knee injury had increased knee valgus during a single-leg drop vertical jump compared to uninjured athletes. Hip abductor strength controls femoral abduction, a component of knee valgus, and hip abductor weakness can predict non-contact anterior cruciate ligament injuries. These studies suggest that knee valgus and hip abductor weakness are risk factors of knee injuries, but they have not been examined for their relationship to upper extremity injuries in baseball. The lower extremities and trunk are critical for the development of force during throwing and altered movement patterns can negatively affect force transfer in the kinetic chain. Knee valgus may lead to an unstable base of support that decreases force transmission to the shoulder and elbow and results in compensating that cause increased forces at these joints.

### Table 1: Participant demographics. Mean (SD).

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Professional Experience (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitchers n= 68</td>
<td>21.7 (2.2)</td>
<td>187.4 (5.4)</td>
<td>94.7 (12.8)</td>
<td>3.1 (2.4)</td>
</tr>
<tr>
<td>Position Players n= 50</td>
<td>21.4 (1.9)</td>
<td>181.5 (5.9)</td>
<td>86.3 (12.6)</td>
<td>2.2 (1.4)</td>
</tr>
<tr>
<td>All Players n=118</td>
<td>21.6 (2.0)</td>
<td>184.4 (6.8)</td>
<td>90.5 (13.3)</td>
<td>2.6 (2.0)</td>
</tr>
</tbody>
</table>
Moreover, poor lumbopelvic control is related to a higher horizontal and elbow valgus torques during pitching. In single-leg stance on the trail leg and increased shoulder and elbow valgus torques during the wind-up and early cocking phases. Abnormalities in pelvic motion can lead to kinetic chain alterations. Hip abduction weakness. However, the clinical significance of these findings is unknown.

A recent study reported relationships between deficits in lumbopelvic control during single-leg stance on the trail leg and increased shoulder horizontal and elbow valgus torques during pitching. Moreover, poor lumbopelvic control is related to a higher likelihood of missing more than 30 days due to an upper extremity injury and reducing pitching performance. Pitchers with better lumbopelvic control had fewer walks and hits per inning and more innings pitched during the season. The current study is one of the few to directly observe lumbopelvic motion in a functional dynamic task, and the first to relate these deficits in pelvic motion to hip abduction weakness. However, the clinical significance of these findings is unknown.

There was no relationship between hip abduction strength and deficits in knee valgus and pelvic drop in position players. This may in part because position players do not throw off the mound as pitchers do. Moreover, position players likely have more movement variability than pitchers, as their throwing patterns vary with throws from a variety of distances and positions. Perhaps the repetitive and consistent nature of pitching contributed to decreased movement coordination in the pitchers in responding to a novel task like the SLSD. Additional data collection including the number of sports played previously and number of years in each individual sport may provide insight into the effect of individual movement variability on lower extremity and trunk kinematics.

### Table 2: Mean (SD) for all variables, and correlations between hip abduction strength and single-leg step-down (SLSD) measures for pitchers and position players.

<table>
<thead>
<tr>
<th></th>
<th>Hip ABD torque</th>
<th>Trunk Lateral Flexion</th>
<th>Trunk Flexion</th>
<th>Pelvis Drop</th>
<th>Knee Valgus (FPPA)</th>
<th>Hip Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Players – lead leg</td>
<td>176.0 (46.6)</td>
<td>4.0 (2.8)</td>
<td>24.2 (10.0)</td>
<td>-6.5 (3.3)</td>
<td>170.3 (5.8)</td>
<td>46.5 (5.6)</td>
</tr>
<tr>
<td>Correlation with hip abd torque</td>
<td>-0.01 (p=0.957)</td>
<td>0.09 (p=0.359)</td>
<td>-0.05 (p=0.589)</td>
<td>0.090 (p=0.337)</td>
<td>-0.01 (p=0.919)</td>
<td></td>
</tr>
<tr>
<td>All Players – trail leg</td>
<td>179.8 (41.0)</td>
<td>4.5 (3.4)</td>
<td>24.0 (10.0)</td>
<td>-6.4 (3.2)</td>
<td>168.2 (6.6)</td>
<td>44.2 (5.6)</td>
</tr>
<tr>
<td>Correlation with hip abd torque</td>
<td>0.03 (p=0.778)</td>
<td>0.05 (p=0.578)</td>
<td>-0.13 (p=0.155)</td>
<td>0.00 (p=0.985)</td>
<td>-0.09 (p=0.317)</td>
<td></td>
</tr>
<tr>
<td>Pitchers – lead leg</td>
<td>163.3 (39.4)</td>
<td>3.4 (2.7)</td>
<td>22.2 (9.6)</td>
<td>-6.0 (3.1)</td>
<td>169.9 (5.8)</td>
<td>47.5 (5.9)</td>
</tr>
<tr>
<td>Correlation with hip abd torque</td>
<td>0.01 (p=0.937)</td>
<td>0.08 (p=0.540)</td>
<td>-0.19 (p=0.116)</td>
<td>0.24* (p=0.049)</td>
<td>0.11 (p=0.387)</td>
<td></td>
</tr>
<tr>
<td>Pitchers – trail leg</td>
<td>166.32 (35.02)</td>
<td>4.1 (3.7)</td>
<td>21.9 (10.0)</td>
<td>-6.7 (3.3)</td>
<td>167.9 (6.6)</td>
<td>44.8 (5.7)</td>
</tr>
<tr>
<td>Correlation with hip abd torque</td>
<td>0.09 (p=0.488)</td>
<td>0.05 (p=0.692)</td>
<td>-0.28* (p=0.021)</td>
<td>0.15 (p=0.232)</td>
<td>-0.12 (p=0.341)</td>
<td></td>
</tr>
<tr>
<td>Position – lead leg</td>
<td>191.79 (50.35)</td>
<td>4.6 (2.9)</td>
<td>26.7 (9.9)</td>
<td>-7.2 (3.3)</td>
<td>170.9 (5.8)</td>
<td>45.2 (4.9)</td>
</tr>
<tr>
<td>Correlation with hip abd torque</td>
<td>-0.16 (p=0.262)</td>
<td>-0.09 (p=0.549)</td>
<td>0.22 (p=0.134)</td>
<td>-0.11 (p=0.461)</td>
<td>0.00 (p=0.993)</td>
<td></td>
</tr>
<tr>
<td>Position – trail leg</td>
<td>196.6 (42.0)</td>
<td>5.1 (2.9)</td>
<td>26.7 (9.5)</td>
<td>-5.97 (3.0)</td>
<td>168.5 (6.6)</td>
<td>43.3 (5.5)</td>
</tr>
<tr>
<td>Correlation with hip abd torque</td>
<td>-0.21 (p=0.144)</td>
<td>-0.15 (p=0.292)</td>
<td>-0.11 (p=0.453)</td>
<td>-0.20 (p=0.170)</td>
<td>0.04 (p=0.805)</td>
<td></td>
</tr>
</tbody>
</table>

ABD=abduction; FPPA= frontal plane projection angle
*Correlation is significant at the 0.05 level (2-tailed)
No deficits in trunk control during the SLSD were found. Trunk control is critical during throwing, as greater trunk lean is related to increased shoulder and elbow joint kinetics during pitching. Poor trunk control may contribute to injury at the shoulder and elbow. Trunk lean detected during a dynamic task such as a SLSD or similarly a single-leg squat can detect trunk lean deficits during pitching. Plummer et al. found a correlation between trunk lean during the single-leg squat and the amount of trunk lean during pitching (r=0.53; p<0.001). However, the factors that contributed to trunk movement deficits in the single-leg squat and pitching were not clear. Interestingly, in the current study, trunk lean was not related to hip abduction strength in pitchers or position players. This is surprising due to the observed relationship with pelvic drop. Theoretically if pitchers with decreased hip abduction strength had increased pelvic drop, one would expect a compensatory increase in trunk lean. It is important to establish the relationship between kinematics observed in a clinical test, and kinematics observed during pitching to identify pitchers that have underlying movement deficits without the need of advanced motion capture systems.

There are several limitations of this study to be considered when interpreting the results. A dynamic task that relates to throwing was measured, but throwing was not directly observed. While the SLSD is a dynamic and reliable clinical assessment, it may not load the hip abductors enough to demonstrate more widespread joint deficits seen in throwing. Strength is not the only reason for altered kinematics; motor control has a major role in the coordination of athletic tasks. The significant, but relatively low correlation values between movement deficits and hip abductor strength suggests other physical factors need to be assessed. This study is the first step in understanding the relationship between muscle capacity (strength) and movement deficits in pitchers. To fully understand the relationship of trunk or lower extremity motion deficits, future research should aim to compare the effects of weakness in multiple lower extremity muscles and the trunk during throwing. Another limitation is that a subgroup analysis was not performed for position players due to low sample sizes for certain positions. Future research should also aim to examine the ability of the SLSD and other clinical screening tests, such as a lateral step down or single-leg balance test, to identify deficits that may increase risk of injury for position players and pitchers.

CONCLUSIONS

The SLSD can be used as a screening tool to allow clinicians to identify movement deficits related to hip abduction weakness. The results of the current study indicate that pitchers with decreased hip abduction strength had increased knee valgus and pelvic drop during performance of a SLSD. Increased knee valgus and pelvic drop may be related to poor lumbopelvic control. Previous studies have reported that professional pitchers with poor lumbopelvic control have decreased performance and greater time lost from participation. Identifying pitchers with deficits in lumbopelvic control through the use of screening tests that do not require the use of three-dimensional motion analysis is valuable for clinicians who work with baseball players. The SLSD can be used to identify movement deficits and allow for the use of preventative training programs that target these deficits. If movement deficits can be addressed, then pitchers may improve pitching performance and have a decreased risk of injury.

CONFLICTS OF INTEREST

The authors affirm that they have no financial affiliation that has direct financial interest in any matter included in this manuscript, except as cited in the manuscript. The authors affirm they have no other conflicts of interest.

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Original Research

Comparison of Common Methodologies for the Determination of Knee Flexor Muscle Strength

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Keywords: strength assessment, nordic hamstring curl, muscle strength, knee flexion, hamstrings, dynamometry

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Background

Knee flexion strength may hold important clinical implications for the determination of injury risk and readiness to return to sport following injury and orthopedic surgery. A wide array of testing methodologies and positioning options are available that require validation prior to clinical integration. The purpose of this study was to 1) investigate the validity and test-retest reliability of isometric knee flexion strength measured by a fixed handheld dynamometer (HHD) apparatus compared to a Biodex Dynamometer (BD), 2) determine the impact of body position (seated versus supine) and foot position (plantar- vs dorsiflexed) on knee flexion peak torque and 3) establish the validity and test-retest reliability of the NordBord Hamstring Dynamometer.

Study Design

Validity and reliability study, test-retest design.

Methods

Forty-four healthy participants (aged 27 ± 4.8 years) were assessed by two raters over two testing sessions separated by three to seven days. Maximal isometric knee flexion in the seated and supine position at 90° knee flexion was measured with both a BD and an externally fixed HHD with the foot held in maximal dorsiflexion or in plantar flexion. The validity and test-retest reliability of eccentric knee flexor strength on the NordBord hamstring dynamometer was assessed and compared with isometric strength on the BD.

Results

Level of agreement between HHD and BD torque demonstrated low bias (bias -0.33 Nm, SD of bias 13.5 Nm; 95% LOA 26.13 Nm, -26.79 Nm). Interrater reliability of the HHD was high, varying slightly with body position (ICC range 0.9-0.97, n=44). Isometric knee flexion torque was higher in the seated versus supine position and with the foot dorsiflexed versus plantarflexed. Eccentric knee flexion torque had a high degree of correlation with isometric knee flexion torque as measured via the BD (r=0.61-0.86). The NordBord had high test-retest reliability (0.995 (95%CI 0.983-0.997, n=19) for eccentric knee flexor strength, with an MDC95 of 26.88 N and 28.76 N for the left and right limbs respectively.

Conclusion

Common measures of maximal isometric knee flexion display high levels of correlation and test-retest reliability. However, values obtained by an externally fixed HHD are not interchangeable with values obtained via the BD. Foot and body position should be considered and controlled during testing.
Comparison of Common Methodologies for the Determination of Knee Flexor Muscle Strength

Level of Evidence
2b

INTRODUCTION

Impairment of muscular strength is linked to functional disability,1 and measurement in a clinical setting may be useful to identify those at increased risk of injury or readiness to return to sport or work following injury. Clinically, muscular strength can be assessed with different methodologies with manual muscle testing (MMT), hand-held dynamometry (HHD) and isokinetic dynamometry representing more common techniques alongside new technologies such as the NordBord Hamstring Dynamometer.1 MMT is a subjective measure that evaluates strength of specific muscle groups against resistance provided by the clinician. Strength is graded on a scale from zero (unable to produced measurable muscle activity) to five (strong resistance) based on the clinician’s subjective perception of the degree of provided resistance. Unfortunately, this technique lacks the precision that is required in clinical cases such as return to sport assessment, where between-limb differences of 10% may be clinically relevant, yet undetectable through MMT.2

Isokinetic dynamometers are considered the gold standard for strength testing as they have been tested for validity and reliability3–5 and can test multiple muscle actions (isokinetic, isometric, isotonic). However, they are expensive and space consuming, which may limit their use.6 Given the imprecision of MMT and the expense of an isokinetic dynamometer, testing with HHD is becoming more common due to its ease in testing, reproducibility, and reduced cost.6,7

Previous authors have reported good to excellent inter- and intra-rater reliability for clinician-stabilized HHD and a high degree of correlation with isokinetic dynamometry,8 yet some concerns remain with this technique.1,7,9 Clinician-stabilized HHD has good agreement with isokinetic dynamometry,3,9–12 however variations in correlations can be expected given that differing contraction modes are often tested (i.e. isometric HHD against isokinetic concentric/eccentric actions).9 The inability to maintain a stable isometric contraction during testing on the part of the clinicians or patient can lead to unreliable and imprecise results. Kelln et al15 suggest that with increasing levels of movement difficulty or strength output, HHD measurements become less reliable. As such, strength of the tester may be a limiting factor for MMT and HHD as well as lack of stabilization of the tester, subject, and device, especially when measuring stronger muscle groups.14,15 If testers of different sexes perform the same measurements, the inter-tester reliability can be questioned when using HHD, especially when testing larger muscles.15,16 This may contribute to the wide range of standard error of measurements (SEM) that have been observed across the literature (SEM 3.8–13.5%).17 Despite these concerns, many authors report moderate to high levels of concurrent validity with isokinetic dynamometers8 and acceptable inter- and intra-rater reliability when comparing HHD to isokinetic dynamometers.

Anchoring the HHD to an immovable object may address the limitations of clinician-stabilized HHD.3,5,6,18–21 Various iterations of stabilization have been used, from engineered metallic frames,22,23 strapping the dynamometer to an immovable object,9,24,25 or bracing using PVC pipes.26 By externally ‘bracing’ the dynamometer, instead of holding it while the subject exerts their maximal force against it, the results are no longer dependent on either the examiner or the subject’s strength.1 Not surprisingly, devices that provide stability to the dynamometer are associated with good to excellent intra-tester and inter-tester reliability; however, the majority of studies have focused on the hip with fewer regarding the knee flexors.9,12,19,24 Agreement between fixed and instrumented dynamometry is variable depending on contraction mode, device tested and muscles evaluated.12,24,25 Kim et al19 found that correlation in knee flexor peak torque was greater when fixed versus clinician stabilized HHD alone when compared with isokinetic dynamometry. Recently Martins et al25 found fixed HHD to show moderate to high correlation with isokinetic dynamometry, yet absolute values are likely not interchangeable between the devices. Consequently, further validation is required for externally fixed-HHD, considering both the validity and agreement with isokinetic dynamometry.

Strength assessment of the hamstrings is complicated due to the anatomical complexity of the muscle group. Differences in torque have been noted with the highest values occurring in the seated as compared with supine and prone positions27,28 which may be attributable to alterations in length and utilization of differing components of the hamstrings. Generally, knee flexion torque is greater with increasing hip flexion (seated versus supine and prone) and with lower levels of knee flexion. The most common positioning across the literature had the participant seated with the hip at or near 90° flexion, and the knee between 30° and 90° of flexion.1,4,5,11,12,29–37 Only a few studies have positioned participants in prone,3,38,39 or with larger angles of hip flexion to more closely replicate striding position during gait.40 Knee flexion torque may also be influenced by the position of the ankle in dorsi- or plantarflexion as the gastrocnemius is a bi-articular muscle at both the ankle and the knee. Knee flexion moments of the gastrocnemius decrease with knee flexion and increase with greater degrees of dorsiflexion.41 The majority of the literature investigates differing angles at a single joint, when it is apparent that concurrent alterations in hip, knee and ankle position may impact isometric knee flexion torque and potentially, the clinical implications of the test. There is a paucity of research examining the impact of concurrent hip and ankle joint angles on isometric strength testing. Consequently, in addition to considerations of stabilization, clinicians must be aware of the impact of foot and hip position on knee flexion torque.

While HHD appears to be a viable alternative to isokinetic dynamometry, questions remain regarding the validity and reliability of fixed HHD and the NordBord dynamometer and the impact of hip and foot position on isometric knee flexion strength. The purpose of this study
was to 1) investigate the validity and test-retest reliability of isometric knee flexion strength measured by a fixed HHD apparatus compared to a BD, 2) determine the impact of body position (seated versus supine) and foot position (plantar- vs dorsiflexed) on knee flexion peak torque and 3) establish the validity and test-retest reliability of the NordBord Hamstring Dynamometer. It was hypothesized that fixed-HHD would provide a level of agreement with BD that would not permit interchange of values between devices and have high inter-rater reliability. Knee flexor strength was hypothesized to be greater in the seated and dorsiflexed position relative to supine testing with the ankle in plantarflexion. Finally, the NordBord was anticipated to have a low to moderate correlation with isometric testing completed on the BD, given the differences in contraction mode assessed, and have excellent test-retest reliability.

METHODS

SUBJECTS

Forty-four healthy participants (22 males, 22 females, age: 27.1 ± 4.8 years, height: 172.2 ± 9.3 cm, weight: 74.8 ± 13.8 kg, Table 1) with no history of neurological conditions, chronic lower extremity injury or lower extremity reconstructive surgeries participated in two experimental sessions separated by three to seven days. Participants were instructed to maintain their regular activities but to avoid intensive lower extremity training the day immediately prior to both testing sessions. This study was approved by the University of Manitoba Health Research Ethics Board and was completed in accordance to the recommendations of the Declaration of Helsinki. Participants were informed of all study procedures and provided written informed consent prior to participation.

PROCEDURES

At the beginning of each testing day, the participant completed a five-minute warm up on a cycle ergometer at a self-selected pace and resistance, followed by lower body stretching as required. Following the five-minute warm up, participants were tested on a HHD, the BD, and a NordBord in each session. The order of the HHD and BD were randomized in the first session, and this order was maintained on the second testing day. The NordBord was completed at the end of the session both days. The HHD (Chatillon DFX2, Ametek, PA, USA) was externally fixed to the wall by a glass suction cup via two S-biners (Nite-Ize, Boulder, CO, USA) each rated to 100 pounds of tension and the suction cup was secured to a metal sheet affixed to the wall. The HHD was outfitted with a hook-shaped clip insert that allowed an inelastic Velcro strap that looped around the participant’s lower limb to connect to the HHD via a metal loop (Figure 1).

Testing was also performed on an isokinetic dynamometer (Biodex System3, Biodex Medical Systems, Shirley, NY) and eccentric knee flexion force and torque was measured during the Nordic Hamstring curl with the NordBord Hamstring dynamometer (NordBord; Vald Performance, Newstead, Australia), both operated according to the manufacturer’s recommendations.

Table 1: Participant characteristics

<table>
<thead>
<tr>
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<th>Mean ± SD</th>
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</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>27.18 ± 4.8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.17 ± 9.39</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>74.8 ± 14</td>
</tr>
<tr>
<td>L Shank Length (cm)</td>
<td>40.48 ± 2.11</td>
</tr>
<tr>
<td>R Shank Length (cm)</td>
<td>40.66 ± 2.51</td>
</tr>
</tbody>
</table>

HHD data were collected by three investigators (two per participant) to assess inter-rater reliability, whereas the Biodex and NordBord data were collected by the same single investigator. Device order (BD, HHD, Nordbord) was standardized across days based on the day one randomization whereas rater order and ankle position (plantar flexion vs dorsiflexion) were randomized between sessions. The NordBord test was completed by the same rater at the end of each testing day, and the seated and supine positions were tested on day one and two respectively. Three attempts were provided on each device and position with a five-second hold for isometric actions, a 10-second break between maximal contractions, a 30-second break between different foot positions, and a five-minute break between devices.

SEATED ISOMETRIC STRENGTH PROTOCOL

Testing with the HHD in the seated position consisted of the participant having both hips and knees in 90° flexion with their popliteal fossae approximately two finger widths away from the edge of the therapy bed to negate any bracing effect. A Velcro strap with a metal loop for attachment to the HHD was secured to the participant’s ankle two centimeters proximal to the lateral malleolus, measured from its point of greatest protrusion. The rater adjusted the height of the bed to ensure the line of force from the strap on the HHD was parallel to the floor and perpendicular to the participant’s leg. The rater ensured the participant’s tested knee remained at 90° of flexion, that the participant’s arms were...
Comparison of Common Methodologies for the Determination of Knee Flexor Muscle Strength

at their sides with hands holding the edges of the bed, and that there was no excessive trunk or hip flexion throughout the isometric contractions through all trials.

Positioning in the BD was similar to that of the HHD with the participant seated with their back against a backrest positioned at 90° above the horizontal, their hips and knees in 90° of flexion, and their arms at their sides with their hands holding the handles of the chair. The axis of rotation of the dynamometer lever arm was positioned coaxial to the lateral femoral epicondyle. The shank was fixed to the lever arm two centimeters proximal to the lateral malleolus again, to keep the active lever arm length consistent between devices. Stabilization straps were secured diagonally across the participant’s chest, and across their waist and thigh of the tested leg, to assure accurate, reproducible testing by controlling excessive movement. Once the participant was positioned, they were familiarized with the testing apparatus and performed two practice repetitions (five-second hold) prior to testing.

SUPINE ISOMETRIC STRENGTH PROTOCOL

The participant was positioned in neutral hip alignment (0° hip flexion) and 90° knee flexion, with the other limb positioned in a relaxed position. The rater aligned the subject and HHD in the same manner as outlined for seated testing.

For testing with the BD in the supine position, the participant was laying against the backrest oriented at 5° above the horizontal with their hips at approximately 0° flexion and knees at 90° flexion. The rater again aligned the Biodex System3 and participant in the same fashion as outlined for seated testing.

NORDBORD ECCENTRIC STRENGTH PROTOCOL

Eccentric knee flexor strength was assessed on the NordBord Hamstring dynamometer. Participants were positioned kneeling with their ankles in the posterior hook anchors on the device. They were instructed to stay straight through the hips and trunk, keeping their shoulders as in line with their knees as possible through the entire movement. The participant then began to lean forward, extending at the knee, and lowered themselves toward the ground as low and slow as possible, while pushing up into the hooks as hard as they could with their ankles. When they could no longer maintain this task, the participant released their contraction and caught themselves with their hands on the landing mat.

STATISTICAL ANALYSIS

Peak force (N), and torque (Nm) were recorded from each device. Shank length (cm) of each participant was measured in order to convert force measurements attained from the HHD testing into torque values, to facilitate absolute comparisons between the HHD and the BD results. Three attempts were completed in each position and test (BD, HHD, NordBord) and the average torque (BD, HHD) and force (NordBord) from the three attempts was used in subsequent analysis. Bland-Altman limits of agreement (LOA) analysis were calculated from the difference between test and retest values plotted against the average of the trials, with 95% LOA calculated as 1.96 multiplied by the standard deviation of the difference (Prism Graphpad, CA, USA). A factorial ANOVA was conducted to determine the impact of differing foot position (plantar flexed (PF) or dorsiflexed (DF), body position (seated or supine), body side (left and right) and test types (BD, HHD, NordBord) on resultant torque values. Intraclass correlation (ICC) estimates and their 95% confidence intervals were calculated using SPSS (IBM, Armonk, NY, USA). Criterion validity of the HHD and Nordbord were established relative to the BD measures through comparison of Pearson correlation coefficients and ICC. Finally, test-retest reliability of the NordBord was established through consideration of ICCs for the left and right lower extremities (two-way mixed effects, absolute agreement, mean K raters). Statistical significance was considered at p<0.05 where appropriate. ICC values were classified as poor (ICC <0.50), moderate (ICC = 0.5-0.75), good (ICC = 0.75-0.90) or excellent (ICC>0.90). 42 Pearson correlation coefficients were classified as high (r >.70), moderate (r = 0.50-0.70), low (r = 0.30-0.50) and weak (r<0.30).

RESULTS

HBL ALTMAAN LOA ANALYSIS OF ISOMETRIC KNEE FLEXION TORQUE
Bland-Altman LOA analysis of isometric knee flexion torque between HHD and BD found low bias with wide limits of agreement relative to obtained test scores (Bias -0.33 Nm, standard deviation (SD) of bias 13.5 Nm; 95% LOA 26.13 Nm, -26.79 Nm). Given the potential for heteroscedasticity in the comparison of HHD against BD, alternative analysis was run on logarithmic transformed data, yielding comparable bias with narrowed limits of agreement (Bias -0.0007, SD of Bias 0.1169, 95% LOA: -0.2298, -0.2284). Inter-rater reliability of the fixed HHD was high as all but one ICC exceeded 0.9, with minimal variation between the differing testing conditions (body position, foot position; Table 2).

BODY AND FOOT POSITION ON TORQUE

Main effects were found for body (F=1,43) =584.9, p<0.001)) and foot (F=1,43) =57.6, p<0.001) position with greater isometric peak torque found in seated, dorsiflexed positions as opposed to supine, plantar flexed positions with data collapsed by side (left and right) and test type (HHD and BD; Figure 2).

NORDBORD VALIDITY AND TEST-RETEST RELIABILITY

Moderate to high correlations were found between eccentric Nordbord hamstring torque and BD isometric torque, ranging from r=0.61-0.86, varying slightly with body and foot position for the BD (Table 3). Peak eccentric hamstring force during the NordBord Hamstring Curl displayed high test-retest reliability (left leg: 0.993 (95%CI 0.983 – 0.997); right Leg: 0.992 (95%CI 0.979-0.997). MDC95 values for the left and right limb were 26.88 N and 28.76 N respectively (Table 4).
Table 2: Inter-rater reliability of the Handheld Dynamometer across body and foot positions

<table>
<thead>
<tr>
<th>Position</th>
<th>Rater 1 (Nm)</th>
<th>Rater 2 (Nm)</th>
<th>ICC (95%CI)</th>
<th>SEM (Nm)</th>
<th>MDC&lt;sub&gt;95&lt;/sub&gt; (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seated, Dorsiflexed, Left</td>
<td>70.47 ± 26.53</td>
<td>68.39 ± 28.42</td>
<td>0.94 (0.89, 0.97)</td>
<td>6.73</td>
<td>18.65</td>
</tr>
<tr>
<td>Seated, Plantarflexed, Left</td>
<td>62.26 ± 23.23</td>
<td>60.84 ± 24.49</td>
<td>0.93 (0.87, 0.96)</td>
<td>6.31</td>
<td>17.50</td>
</tr>
<tr>
<td>Seated, Dorsiflexed, Right</td>
<td>69.50 ± 26.11</td>
<td>68.32 ± 26.54</td>
<td>0.97 (0.95, 0.99)</td>
<td>4.56</td>
<td>12.64</td>
</tr>
<tr>
<td>Seated, Plantarflexed, Right</td>
<td>62.66 ± 24.87</td>
<td>57.67 ± 22.07</td>
<td>0.93 (0.87, 0.96)</td>
<td>6.21</td>
<td>17.21</td>
</tr>
<tr>
<td>Supine, Dorsiflexed, Left</td>
<td>41.72 ± 14.21</td>
<td>40.82 ± 13.90</td>
<td>0.92 (0.85, 0.96)</td>
<td>3.98</td>
<td>11.02</td>
</tr>
<tr>
<td>Supine, Plantarflexed, Left</td>
<td>31.97 ± 10.54</td>
<td>30.95 ± 11.41</td>
<td>0.92 (0.85, 0.95)</td>
<td>3.1</td>
<td>8.60</td>
</tr>
<tr>
<td>Supine, Dorsiflexed, Right</td>
<td>40.33 ± 13.65</td>
<td>39.79 ± 15.50</td>
<td>0.94 (0.89, 0.97)</td>
<td>3.57</td>
<td>9.89</td>
</tr>
<tr>
<td>Supine, Plantarflexed, Right</td>
<td>32.49 ± 11.88</td>
<td>30.14 ± 11.25</td>
<td>0.90 (0.81, 0.94)</td>
<td>3.66</td>
<td>10.14</td>
</tr>
</tbody>
</table>

ICC=intraclass correlation coefficient, CI=confidence interval, SEM=Standard Error of the Measurement, MDC<sub>95</sub>=Minimum Detectable Change, Nm=Newton-Meter

Table 3: Correlations between Biodex Dynamometer measured isometric knee flexion torque and maximal eccentric knee flexor torque during the Nordic Hamstring Curl exercise

<table>
<thead>
<tr>
<th>Body and Foot Position</th>
<th>Biodex Isometric Torque (Nm)</th>
<th>Nordic Eccentric Torque (Nm)</th>
<th>Pearson Correlation (Sig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seated, Dorsiflexed, Left</td>
<td>71.4 ± 25.80</td>
<td>110.35 ± 47.03</td>
<td>0.665 (p=0.001392)</td>
</tr>
<tr>
<td>Seated, Plantarflexed, Left</td>
<td>61.92 ± 23.15</td>
<td>110.35 ± 47.03</td>
<td>0.608 (p=0.004482)</td>
</tr>
<tr>
<td>Seated, Dorsiflexed, Right</td>
<td>72.01 ± 25.10</td>
<td>107.20 ± 43.41</td>
<td>0.791 (p=0.000003)</td>
</tr>
<tr>
<td>Seated, Plantarflexed, Right</td>
<td>64.24 ± 23.39</td>
<td>107.20 ± 43.41</td>
<td>0.714 (p=0.000407)</td>
</tr>
<tr>
<td>Supine, Dorsiflexed, Left</td>
<td>43.86 ± 17.31</td>
<td>110.35 ± 47.03</td>
<td>0.861 (p=0.000001)</td>
</tr>
<tr>
<td>Supine, Plantarflexed, Left</td>
<td>32.37 ± 13.85</td>
<td>110.35 ± 47.03</td>
<td>0.743 (p=0.000172)</td>
</tr>
<tr>
<td>Supine, Dorsiflexed, Right</td>
<td>45.02 ± 16.36</td>
<td>107.20 ± 43.41</td>
<td>0.791 (p=0.000003)</td>
</tr>
<tr>
<td>Supine, Plantarflexed, Right</td>
<td>33.93 ± 14.40</td>
<td>107.20 ± 43.41</td>
<td>0.702 (p=0.001)</td>
</tr>
</tbody>
</table>

Figure 2: Difference in torque and Log10 difference in torque by foot position

DISCUSSION

The purpose of this study was to: 1) investigate the validity and reliability of isometric knee flexion strength measured with an externally fixed HHD compared to a BD, 2) determine the impact of hip and ankle position on isometric knee flexion strength and 3) assess the validity and test-retest reliability of the NordBord Hamstring Dynamometer.

VALIDITY AND RELIABILITY OF FIXED–HHD

With respect to the validity of fixed-HHD, a moderate to high degree of correlation with the BD was found, consistent with previous studies across various muscle
The magnitude of correlation did not differ substantially between the seated and supine position or with plantar or dorsiflexion. Despite the degree of correlation between the two devices, the limits of agreement spanned more than 50 Nm for the knee flexors. This is consistent with previous data from Lesnak et al\textsuperscript{10} who compared isometric knee extension peak torque between fixed-HHD, finding limits of agreement of 19.4 ± 53.2 Nm, and larger when evaluating rate of torque development. Martins et al\textsuperscript{25} demonstrated comparable correlations between the two machines, with similarly wide limits of agreement for the knee flexors. Katoh et al\textsuperscript{44} found higher forces with isokinetic dynamometers (tested isometrically) than with a belt stabilized HHD. As the design lacked a clinician-stabilized condition, it cannot be concluded that stabilization of the dynamometer improved agreement between BD and HHD. Data from Kim et al\textsuperscript{45} found correlation between the two devices were improved with fixation. Others have suggested that belt fixation is associated with greater force generation than clinician-stabilized conditions, and that HHD may underestimate strength relative to BD.\textsuperscript{19–21,24,25,44,45} Conversely, Lesnak et al\textsuperscript{10} found HHD to overestimate peak torque production yet underestimate the rate of torque development. Nevertheless, these results indicate that while instrumented assessment on isokinetic dynamometers and fixed HHD are correlated, values should not be interchanged between devices.

Inter-rater reliability of the fixed HHD was generally high and consistent with previous literature using fixed HHD for assessment of knee extensors\textsuperscript{12,19} and flexors.\textsuperscript{12,18,19,45,46} Romero-Franco et al\textsuperscript{45} tested a comparable seated knee flexion setup, anchoring the dynamometer to solid wall bars finding an ICC of 0.979 when retesting over a one week period. Differing from the present setup, both Wollin et al\textsuperscript{45} and Thorborg et al\textsuperscript{18} used a strap to anchor the dynamometer to the ground, with the patient near 0°-50° knee flexion in the prone position. While differences in knee flexion strength across the studies may represent differing contributions of components of the hamstring and gastrocnemius, inter-rater reliability was acceptable but lower than the present study (ICC 0.8 (95%CI 0.65-0.93) and ICC 0.87 (95%CI 0.75-0.93)). Kim et al\textsuperscript{45} found fixation of the dynamometer to marginally improve inter-rater reliability against clinician-stabilized for the knee extensors (ICC 0.952 to 0.98 and 0.940 to 0.963 respectively); However, van der Made et al\textsuperscript{46} found fixation did not improve intertester reliability for isometric knee flexion in a cohort of rugby players of increased lower extremity strength, although all ICC values were 0.8 or higher. Nevertheless, this methodology displays excellent inter-rater reliability on par with prior methodologies for fixed-HHD and indicates that HHD is acceptable for clinical use.

**EFFECT OF HIP AND ANKLE POSITION ON KNEE FLEXOR ISOMETRIC STRENGTH**

Given the biarticular structure of semitendinosus, long head biceps femoris, semimembranosus and gastrocnemius, hip, knee and ankle position must be considered when determining isometric knee flexion strength. Across the literature, assessment of knee flexion strength has been completed in the seated, prone and supine positions, although few, if any, direct comparisons of all three positions exist. Additional differences in the assessed contraction modes (i.e. isokinetic, isometric) further confound the comparison of knee flexion strength across studies by body position. In the present comparison of torque by position, collapsed for device (HHD and BD) knee flexion torque was greatest in the seated position with the foot dorsiflexed, and lowest in the supine position with the foot plantarflexed. Prior data evaluating concentric isokinetic strength generally agrees, finding increased torque with increased hip flexion in the seated as compared to the semi-reclined, supine and prone positions that is attributed to optimal positioning on the hamstring length-tension relationship with hip flexion beyond 90\textdegree.\textsuperscript{27,47–50} Consistent with these findings, Miller et al\textsuperscript{51} found an approximate 12% reduction in isokinetic knee flexion torque with the ankle in plantarflexion against dorsiflexion. Marchetti et al\textsuperscript{52} demonstrated a 22% difference in isometric knee flexion favoring the dorsiflexed versus plantar flexed position at 90\textdegree knee flexion, although the magnitude of difference was reduced at 0\textdegree knee flexion. Due to the biarticular nature of the gastrocnemius, plantar flexion of the ankle produces active insufficiency, and thus, reduced knee flexion torque. The values in the present study are lower than those previously observed.\textsuperscript{18,45} This may be attributed to differences between the sampled groups, prone versus supine positioning, and that testing at 90\textdegree knee flexion may result in reduced active contribution from the gastrocnemius, and reliance of differing components of the hamstring complex compared to those testing within lesser degrees of knee flexion.\textsuperscript{47,52–54} It is apparent that knee flexion torque varies with position of the hip, knee and ankle, and future studies should report and control these parameters.

### Table 4: Test-retest reliability and MDC\textsubscript{95} of the NordBord hamstring dynamometer force measurements

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (N)</th>
<th>Test 2 (N)</th>
<th>ICC</th>
<th>SEM (N)</th>
<th>MDC\textsubscript{95} (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>276.98 ± 119.68</td>
<td>274.49 ± 115.42</td>
<td>0.993 (0.98, 0.997)</td>
<td>19.31</td>
<td>26.88</td>
</tr>
<tr>
<td>Right</td>
<td>269.32 ± 112.10</td>
<td>271.93 ± 116.63</td>
<td>0.992 (0.97, 0.997)</td>
<td>13.66</td>
<td>28.76</td>
</tr>
</tbody>
</table>

ICC=intraclass correlation coefficient, CI=confidence interval, SEM=Standard Error of the Measurement, MDC\textsubscript{95}=Minimum Detectable Change, Nm=Newton-Meter
VALIDITY AND RELIABILITY OF THE NORDBORD HAMSTRING DYNAMOMETER

Few studies have evaluated the NordBord Hamstring dynamometer against other methodologies of strength assessment like the isokinetic dynamometer or isometric HHD. These data indicate a strong correlation between isometric knee flexion and eccentric knee flexion torque during the Nordic Hamstring curl. The relationship between torque during the Nordic hamstring curl and isokinetic dynamometry is equivocal. Van Dyk et al. found a poor degree of correlation between seated concentric and eccentric isokinetic knee flexion at 60°/s and 300°/s and eccentric Nordic hamstring curl torque. The authors attributed this to the characteristics of the tasks, whereby the hip is in a relatively neutral position during the Nordic hamstring curl as compared to unilateral isokinetic measures. Conversely, Lodge et al. assessed a comparable Nordic dynamometer (Hamstring Solo Elite) and found an inter-device correlation of 0.823 and 0.840 between the left and right limbs with isokinetic eccentric knee flexion torque at 30°/s. Our data may partially support this assertion, as the range and degree of correlations were slightly higher in the supine, hip neutral position as compared to the seated position. Inter-rater reliability of the NordBord exceeded the previously published values and is comparable to those observed by Lodge et al. for the Hamstring Solo dynamometer. Consequently, the NordBord shows high test-retest reliability and a moderate correlation with isometric knee flexion assessed with the BD. Further work is required to clarify the relationship between differing test methodologies by body position and contraction mode.

LIMITATIONS

Although foot position was controlled for during the BD and HHD trials, it was not rigidly monitored during completion of the Nordic Hamstring Curl on the NordBord. Participants were given standardized instructions for positioning on the device that started with the foot in a neutral position; however, foot position was not specifically controlled during completion of the repetition. While foot position has been shown to be inconsequential for EMG amplitude in biceps femoris and the medial gastrocnemius, data on force production is lacking. A further limitation is that as we counterbalanced body position across testing days, our design did not allow for the determination of test-retest reliability for the externally fixed HHD.

CONCLUSION

The results of the present study serve to establish the validity of externally fixed HHD for the assessment of knee flexion strength against the BD. Wide limits of agreement despite low bias suggest that these values should not be interchanged between devices. As expected, inter-rater reliability of externally fixed HHD was also high. The position of the hip, knee and ankle must be considered as this may influence torque developed by the knee flexors. Future research is required to conclusively determine whether selective activation or utilization of the knee flexors may contribute to the differential in torque production, beyond changes in muscle length alone. The NordBord displayed moderate correlation with the BD despite testing differing contraction modes, and excellent test-retest reliability. Ultimately, clinicians have various options available to them for the measurement of knee flexion strength, but must determine whether variation in testing device, contraction mode, and body position are relevant to the clinical issue at hand. Nevertheless, fixed HHD is valid and reliable for the assessment of knee flexor strength and is therefore a useful tool for clinicians who do not have access to other assessment methodologies such as isokinetic dynamometry.

ACKNOWLEDGMENTS

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CONFLICTS OF INTEREST

The authors have no conflicts to declare.

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REFERENCES


The Single Leg Squat Test: A “Top-Down” or “Bottom-Up” Functional Performance Test?

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Keywords: ankle, foot posture, functional performance test, lower extremity, movement system

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Background
Medial knee deviation (MKD) during the single leg squat test (SLST) is a common clinical finding that is often attributed to impairments of proximal muscular structures. Investigations into the relationship between MKD and the foot and ankle complex have provided conflicting results, which may impact clinicians’ interpretation of the SLST.

Purpose
The purpose of this study was to compare ankle dorsiflexion range of motion (ROM) and foot posture in subjects that perform the SLST with MKD (fail) versus without MKD (pass).

Hypothesis
There will be a difference in ankle dorsiflexion ROM and/or foot posture between healthy individuals that pass and fail the SLST for MKD.

Study Design
Cross-sectional study.

Methods
Sixty-five healthy, active volunteers (sex = 50 female, 15 male; age = 25.2 +/- 5.6 years; height = 1.7 +/- .1 m; weight = 68.5 +/- 13.5 kg) who demonstrated static balance and hip abductor strength sufficient for performance of the SLST participated in the study. Subjects were divided into pass and fail groups based on visual observation of MKD during the SLST. Foot Posture Index (FPI-6) scores and measures of non-weight bearing and weight bearing active ankle dorsiflexion (ROM) were compared.

Results
There were 33 individuals in the pass group and 32 in the fail group. The groups were similar on age (p = .899), sex (p = .341), BMI (p = .818), and Tegner Activity Scale score (p = .456). There were no statistically significant differences between the groups on the FPI-6 (pass group mean = 2.5 +/- 3.9; fail group mean = 2.3 +/- 3.5; p = .599), or any of the measures of dorsiflexion range of motion (non-weight bearing dorsiflexion with knee extended: pass group = 6.9° +/- 5.7°, fail group = 7.8° +/- 3.0°; non-weight bearing dorsiflexion with knee flexed: pass group = 13.5° +/- 5.6°, fail group = 13.9° +/- 5.3°; weight bearing dorsiflexion: pass group = 42.7° +/- 6.0°, 42.7° +/- 8.3°, p = .611).

Conclusions
Failure on the SLST is not related to differences in clinical measures of active dorsiflexion ROM or foot posture in young, healthy individuals. These findings suggest that clinicians...
may continue using the SLST to assess neuromuscular performance of the trunk, hip, and knee without ankle dorsiflexion ROM or foot posture contributing to results.

**Level of Evidence**

Level 3.

**INTRODUCTION**

The single leg squat test (SLST) is a functional performance test that is used by clinicians and researchers to assess neuromuscular performance of the trunk and lower extremity. The SLST is commonly used for injury prevention screening and physical rehabilitation evaluation. The test has been applied to individuals with non-arthritic hip pain, patellofemoral pain syndrome, knee osteoarthritis, and anterior cruciate ligament (ACL) reconstruction. Excessive medial knee deviation (MKD) during the eccentric phase of the squat is a common finding and is used as a marker of aberrant movement patterns in both visual rating scales and kinematic measurements. The presence of increased MKD has been related to common lower extremity dysfunctions such as non-arthritic hip pain, anterior knee pain, and increased risk of noncontact ACL injury.

Clinicians and researchers commonly associate excessive MKD with poor motor control of the muscular structures proximal to the knee joint. It has been determined that individuals who display excessive MKD during single limb standing activities utilize different activation patterns of the hip abductors and adductors, and demonstrate differences in strength measures of the hip extensors, lateral rotators, and abductors. This "top-down" rationale for MKD leads clinicians to implement treatment programs that emphasize hip-focused neuromuscular control and strength training.

Another possible explanation for MKD, however, is that it could occur as a result of impairments at the foot and ankle. This "bottom-up" approach to explaining MKD may be associated with abnormal foot posture, such as increased/decreased medial arch height, excessive calcaneal inversion/eversion, or differences in talar navicular bulge. Abnormal foot posture has been reported to influence the biomechanics of the lower extremity during weightbearing and has been related to proximal musculoskeletal dysfunction such as low back pain and hip pain. Given the associations between foot posture, weightbearing biomechanics, and proximal musculoskeletal dysfunction, it is possible that foot posture may be a factor in performance of the SLST.

Ankle range of motion (ROM) may also influence proximal movement patterns in the closed kinetic chain. Sagittal plane ROM restrictions of the lower extremity joints have been associated with the presence of increased MKD during weight-bearing functional performance tests. Decreased passive ROM into ankle dorsiflexion with the knee flexed and extended has been reported in individuals that perform the overhead squat with excessive MKD. However, the evidence regarding the association between ankle dorsiflexion and MKD is not definitive. Both Bell et al. and Dill et al. found no relationship between MKD during functional tests and ankle dorsiflexion ROM. This conflicting evidence suggests that more study is needed to understand the association between ankle dorsiflexion ROM and MKD during weightbearing functional tests.

The lack of evidence relating ankle dorsiflexion ROM and foot posture to MKD during weightbearing functional tests may impact clinical practice. Individuals who have normal strength and activation of muscles of the hip and who do not improve in their ability to perform a SLST with a "top-down" focused rehabilitation program may have contributing foot and ankle impairments, such as restricted ankle dorsiflexion ROM or abnormal foot posture. Therefore, the purpose of this study was to compare ankle dorsiflexion ROM and foot posture in subjects that perform the SLST with MKD (fail) versus without MKD (pass). The primary hypothesis was that subjects that failed the SLST for MKD would have different foot posture and/or a different amount of active ankle dorsiflexion ROM than those that did not fail for MKD.

**METHODS**

**STUDY DESIGN**

This was a cross-sectional, laboratory-based investigation that compared ankle dorsiflexion ROM (non-weight bearing with the knee extended (DF-NWB-ext), non-weight bearing with the knee flexed (DF-NWB-flx), and weight bearing using the weight-bearing lunge (WBL)) and foot posture between those that perform the SLST with and without MKD. Based on previous work on the association of ankle dorsiflexion range of motion with MKD during the SLST, power was calculated to be 80% with 26 subjects per group, at an alpha level of 0.05, with an effect size of 0.70. Subject recruitment and data collection took place from August 2019 to December 2019. This study was undertaken with approval from Duquesne University's institutional review board.

**SUBJECTS**

Healthy, active volunteers were recruited for this study. To be included, subjects had to be between the ages of 18 and 45 years, report an activity level of ≥ 3 on the Tegner Activity Scale, be able to: 1) perform a vertical drop jump; 2) complete the screening protocol; and 3) read and communicate in English. Subjects were excluded if they had inadequate hip muscle function as measured by the following criteria: 1) unable to maintain single leg stance for ≥ 30 seconds without a Trendelenburg or compensated Trendelenburg posture; 2) <4/5 hip abductor strength on the test extremity by manual muscle test. Subjects were also excluded if they: 3) were pregnant; 4) experienced a lower extremity injury on the side being tested within the prior six months that limited activity for ≥ 2 days; or 5) underwent lower extremity surgery on the side being tested in the prior year. (Table 1)
Table 1: Inclusion/exclusion criteria.

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Between 18-45 years old</td>
<td>• History of a lower extremity injury on the side being tested in the past 6 months that limited physical activity for ≥2 days</td>
</tr>
<tr>
<td>• Tegner Activity Scale score &gt; 3</td>
<td>• Had surgery on the lower extremity that was being tested in the past year</td>
</tr>
<tr>
<td>• Physically capable of:</td>
<td>• Unable to maintain single leg stance for 30 seconds with a level pelvis and neutral trunk</td>
</tr>
<tr>
<td>◦ Performing the SLST</td>
<td>• &lt; 4/5 strength of the hip abductors</td>
</tr>
<tr>
<td>◦ Performing a drop vertical jump</td>
<td>• Known pregnancy</td>
</tr>
<tr>
<td>• Able to read and communicate in English</td>
<td></td>
</tr>
</tbody>
</table>

PROCEDURES

After providing informed consent, subjects reported their age, sex, height, and weight and then completed the Tegner Activity Scale and the Lower Extremity Functional Scale (LEFS). Subjects then completed the dominant extremity test and screening protocol. To determine dominant extremity, subjects performed five unilateral drop jump landings using a previously published protocol. The lower extremity that was chosen for landing in ≥ 3 of 5 landings was determined to be the dominant extremity and used for testing.

After this, each subject participated in a screening protocol to determine whether they had grossly sufficient balance, neuromuscular control, and hip abductor strength to perform the SLST. The screening protocol consisted of three tasks: (1) 30 seconds of single leg stance on the test extremity; (2) five squats performed in a bilateral fashion; (3) manual muscle test of the hip abductors. During the single leg stance test, subjects’ balance and ability to maintain a level pelvis and neutral trunk were assessed so that balance and gross strength deficits of the hip abductors could be clinically ruled out as contributors to MKD on the SLST. Subjects failed this portion of the screening test if they touched the floor with the non-dominant extremity or if a Trendelenburg/compensated Trendelenburg position (Figure 1A-B) was identified by the investigator (LC).

If subjects failed this portion of the testing due to loss of balance, they were given a second opportunity to pass. If subjects failed on the second trial, they were excluded from the study. The second portion of the screening protocol consisted of subjects performing five bilateral bodyweight squats to approximately 90° of knee flexion in order to determine whether the subject was physically capable of performing the SLST. The investigator (LC), a practicing physical therapist with over nine years of clinical experience and board certification in orthopedic physical therapy, excluded subjects if the squats were performed with gross asymmetry, poor control, or aberrant movement patterns that would preclude them from being able to perform the clinical SLST protocol. If subjects passed the bodyweight squat test, a manual muscle test of the hip abductors was performed to ensure that included subjects had at least 4/5 strength. (Figure 2)

After passing the screening process, subjects were instructed in the evidence-based SLST protocol. This SLST protocol was developed in a systematic review of 42 peer-reviewed and published manuscripts and was chosen for this study because it is reflective of how the SLST is commonly performed clinically. This protocol does not require equipment or time-consuming set-up and visual assessment of subject performance has been shown to be reliable. To perform the SLST, a "T" (6’ horizontal, 10’ vertical)
Figure 3A-B: Performance of the clinical single leg squat test (SLST) protocol. A. Starting position. B. Squat position.

Figure 4A-B: A. Goniometric measurement of non-weight bearing dorsiflexion with the knee extended. B. Goniometric measurement of prone non-weight bearing dorsiflexion with the knee flexed.

Ankle dorsiflexion ROM measurements were then taken using three different techniques: (1) active, non-weight bearing, subtalar neutral, with the knee positioned in 0° of extension (DF-NWB-ext), (2) active, non-weight-bearing, subtalar neutral, with the knee flexed to 90° (DF-NWB-flx), and (3) weight-bearing lunge test (WBL). These measurements were chosen based on their clinical relevance and their use in previous studies. Non-weight bearing measurements were taken using a 12-inch universal goniometer (Sammons Preston Rolyan, Bolingbrook, IL) and the weight-bearing measurement was taken with a digital inclinometer (Baseline, Fabrication Enterprises Inc., New York, NY). DF-NWB-ext was measured in long sitting with the knee extended to 0° and DF-NWB-flx was measured in prone with the knee flexed to 90°. For both DF-NWB-ext and DF-NWB-flx, subjects were asked to perform maximal active ankle dorsiflexion, were positioned in subtalar neutral by the investigator, and then range of motion was measured with a goniometer. For the WBL, participants placed their test extremity on a piece of athletic tape that was placed perpendicular to a wall. Subjects were instructed to keep their toes and heel on the tape in order to prevent toe-out or toe-in positioning during the measurement. The digital inclinometer was placed 15 cm below the tibial tuberosity and subjects were instructed to lunge forward on the test extremity until their heel began to lift off the floor. Participants informed the investigator when the heel began to lift off the floor and the amount of dorsiflexion present at this time was recorded. All dorsiflexion measurements were performed by one investigator, who took three measurements in each position. The average of the three measurements was used for analysis. Intra-rater reliability was excellent for all of the dorsiflexion measures (DF-NWB-ext: intraclass correlation coefficient (ICC(3,3)) = .909, standard error of measurement (SEM) = 1.043°; DF-NWB-flx: ICC(3,3) = .967, SEM = .984°; WBL: ICC(3,3) = .885, SEM = 2.535°).

Subjects then performed five repetitions of the single leg squat while being video recorded using an iPad Pro 11” (Apple, Cupertino, CA). The iPad Pro was held two meters in front of the subject and 0.9 meters from the floor. Videos were analyzed for group assignment by two independent physical therapists (one with 20 years of clinical experience in outpatient orthopedics and board certification in orthopedic and sports physical therapy (BK); and another with five years of clinical experience in outpatient orthopedics and board certification in orthopedic physical therapy (AD)). These researchers were blinded to subjects’ other data points. Subjects whose patella deviated medial to the second toe on ≥ 3 of their five squat attempts were placed in the fail group. All other subjects were placed into the pass group. Raters met to review discrepancies and together determined subjects’ final group assignment so that there was complete agreement for final group assignment.

STATISTICAL METHODS

Statistical analysis was completed using SPSS Statistics version 26 (IBM Corporation, Armonk, NY). The pass and fail groups were compared using independent samples t-tests.
Table 2: Demographic data by group. Values reported are mean +/- standard deviation unless otherwise noted. Subjects whose patella deviated medial to the second toe on ≥ 3 of their five squat attempts were placed in the fail group. All other subjects were placed into the pass group.

<table>
<thead>
<tr>
<th></th>
<th>Sample (n = 65)</th>
<th>Pass (n = 33)</th>
<th>Fail (n = 32)</th>
<th>p-value (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 females (77%)</td>
<td>27 females (82%)</td>
<td>23 females (72%)</td>
<td>0.341</td>
</tr>
<tr>
<td></td>
<td>15 males (23%)</td>
<td>6 males (18%)</td>
<td>9 males (28%)</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>25.2 +/- 5.6</td>
<td>25.2 +/- 5.5</td>
<td>25.1 +/- 5.9</td>
<td>0.899</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>23.7 +/- 4.1</td>
<td>23.6 +/- 3.7</td>
<td>23.9 +/- 4.5</td>
<td>0.818</td>
</tr>
<tr>
<td>Tegner Activity Scale score</td>
<td>5.8 +/- 1.4</td>
<td>5.6 +/- 1.3</td>
<td>5.9 +/- 1.6</td>
<td>0.456</td>
</tr>
<tr>
<td>Lower Extremity Functional Scale score</td>
<td>Median = 80 Mean = 79.46 +/- 1.5</td>
<td>Median = 80 Mean = 79.9 +/- 0.4</td>
<td>Median = 80 Mean = 79.0 +/- 1.9</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 3: Clinical characteristics of the foot and ankle by group. Values reported are mean +/- standard deviation. Subjects whose patella deviated medial to the second toe on ≥ 3 of their five squat attempts were placed in the fail group. All other subjects were placed into the pass group.

<table>
<thead>
<tr>
<th></th>
<th>Pass (n = 39)</th>
<th>Fail (n = 26)</th>
<th>p-value (2 tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Posture Index</td>
<td>2.49 +/- 3.9</td>
<td>2.30 +/- 3.5</td>
<td>0.599</td>
</tr>
<tr>
<td>Dorsiflexion, non-weight bearing, knee extended</td>
<td>6.9° +/- 3.7°</td>
<td>7.8° +/- 3.0°</td>
<td>0.611</td>
</tr>
<tr>
<td>Dorsiflexion, non-weight bearing, knee flexed</td>
<td>13.5° +/- 5.6°</td>
<td>13.9° +/- 5.3°</td>
<td>0.611</td>
</tr>
<tr>
<td>Weight bearing dorsiflexion</td>
<td>42.7° +/- 6.0°</td>
<td>42.7° +/- 8.3°</td>
<td>0.611</td>
</tr>
</tbody>
</table>

RESULTS

Seventy subjects were recruited for the study and data from 65 subjects was used for the analysis. One subject was excluded due to pregnancy, one was excluded because they did not score ≥ 3 on the Tegner Activity Scale, two subjects were excluded due to failure during the screening protocol, and one subject was excluded because they were unable to complete data collection due to time constraints. (Figure 5)

There were 32 subjects in the fail group and 33 subjects in the pass group. According to independent samples T-tests, the pass and the fail groups were similar in age (p = .899), sex (p = .341), BMI (p = .818), and Tegner Activity Scale score (p = .456). There was a statistically significant difference between the groups on LEFS score (p = .002). However, this result is not likely clinically meaningful, as median scores for the LEFS were 80 in each group and 100% of subjects in the study scored within the same range of minimal clinically important difference (9 points). Means, standard deviations, and levels of statistical significance for these variables are summarized in Table 2.

The dorsiflexion ROM measures (DF-NWB-ext, DF-NWB-flx, WBL) were found to correlate moderately (r = .497 - .764) and were analyzed using a MANOVA. The MANOVA revealed that there were no differences in ankle dorsiflexion ROM between the groups (p = .611). The FPI-6 did not correlate with the dorsiflexion ROM measures (r = .012) and was analyzed separately using an independent samples T-test. Foot posture was also not different between those that failed and passed the SLST for MKD (p = .599). Means, standard deviations, and significance levels for the clinical characteristics of the foot and ankle are summarized in Table 3.
DISCUSSION

The most important finding of this study was that there were not significant differences in clinical measures of ankle dorsiflexion ROM or foot posture between subjects that passed versus failed the SLST for MKD. The hypothesis of this study was therefore not supported. These results are supported by previous work that has shown that ankle dorsiflexion was not a factor in MKD during other forms of weight-bearing functional testing. The current findings indicate that MKD on the SLST may not be attributed to differences in dorsiflexion ROM or foot posture and support the continued use of the SLST to assess neuromuscular performance of the trunk, hip, and knee.

The key findings of this study that ankle dorsiflexion ROM measures are not different in subjects that perform a functional test with and without MKD are supported by published evidence. Previous work has shown that measures of non-weight-bearing/knee extended ankle dorsiflexion, non-weight-bearing/knee flexed ankle dorsiflexion, and weight-bearing ankle dorsiflexion ROM were not significantly different in individuals that performed the overhead squat with MKD versus those that performed the overhead squat without MKD. Additionally, Dill et al. found no differences in MKD during a double-legged jump landing task or during the SLST between subjects with limited versus normal non-weight-bearing/knee extended ankle dorsiflexion or weight-bearing ankle dorsiflexion measures.

The evidence-based SLST protocol that was used in this study is reflective of typical clinical use of the SLST: subjects’ performance was assessed visually and squat depth was not formally measured. Previous research that reported a difference in ankle dorsiflexion ROM in subjects that failed the SLST utilized varying SLST protocols that required measurement of squat depth to > 60° of knee flexion. It is possible that performing the SLST to > 60° of knee flexion may engage near end range ankle dorsiflexion and may result in frontal and transverse plane compensations that have been reported to occur with restricted sagittal plane motion. Without squatting to a depth that reaches near end range ankle dorsiflexion, increased MKD is unlikely to be impacted by restricted ankle dorsiflexion ROM. Although kinematic data was not gathered during this study, Ageberg et al. utilized a similar SLST protocol and reported squat depth to be less than 45° of peak knee flexion. Ankle dorsiflexion kinematics and ROM measures were not reported in Ageberg et al.’s study, so it is unclear whether patients reached end-range of dorsiflexion. However, a separate study by Whatman et al. reported an average peak knee flexion angle of 65° when subjects were asked to perform a unilateral squat until they reached end-range dorsiflexion. The summary of these findings suggests that, in the current study, subjects likely did not squat to a depth that engaged end-range ankle dorsiflexion and that the observed increase in frontal and transverse plane movement may not be attributed to sagittal plane ROM restrictions of the ankle.

Although an attempt to control for neuromuscular deficits at the hip was implemented for the current study, increased MKD during the SLST is likely related to proximal dysfunction that was undetected by the utilized screening protocol. The use of surface electromyography or handheld dynamometry with normalization to body mass may have better elucidated the proximal neuromuscular deficits contributing to MKD during the SLST. Proximal impairments, such as differences in maximum force production, iso-kinetic torque, and activation patterns of muscles of the hip have been reported in individuals that fail the SLST. Further support of this “top-down” approach to assessing SLST performance can be seen in intervention studies in which treatments targeting proximal muscle function have been shown to improve SLST performance. These factors indicate that the evidence-based SLST protocol used in the current study and commonly implemented in the clinic may best be used to assess proximal, rather than distal, contributors to functional movement of the lower extremity kinetic chain. Furthermore, the results suggest that clinical screening of hip abductor strength by manual muscle test and Trendelenburg test is not adequate to detect a dysfunction that may result in MKD during the SLST. The results of the current study support the continued use of the evidence-based SLST to assess neuromuscular performance of the trunk, hip, and knee not otherwise detected by manual muscle test and Trendelenburg stance without dorsiflexion ROM and foot posture impacting results.

There are limitations to this investigation. First, this study was performed using young, healthy subjects (mean age = 25.2 +/- 5.6 years, range = 19 – 45 years), so results may not be generalizable to populations with musculoskeletal dysfunction or of older or younger age. This study was also limited because the sample was 77% percent female. Although the distribution of sexes between the pass and fail groups was not statistically different, utilizing a sample that is predominantly female could have impacted the study’s results, as there have been reports that females...
and males may perform the SLST differently.\textsuperscript{17,35,62} Additionally, this study was designed to be clinically applicable through the use of common clinical tests and measures, such as goniometry and the FPI-6. The error in some of these measurement techniques and tools is high\textsuperscript{63} and could have impacted the results of the study. A 6\degree - 8\degree change in lower extremity goniometric measurements is needed in order to consider the differences clinically meaningful.\textsuperscript{54,64} Given the relatively small range of physiologic motion available into ankle dorsiflexion (20 degrees\textsuperscript{65}), it is possible that goniometry is not precise enough to detect differences that may exist between groups. Furthermore, the measurement of active non-weight bearing dorsiflexion and passive weight-bearing ankle dorsiflexion resulted in a wide range of ROM measurements being recorded. The use of the bilateral FPI-6 is another limitation to this study. The FPI-6 measures foot posture in static, bilateral weight-bearing and an individual's score on the FPI-6 may not be reflective of their foot posture or function in unilateral stance or during a dynamic unilateral task, such as the SLST. Motion capture data showing triplanar foot and ankle kinematics may offer more information regarding foot and ankle movement during the SLST. Another limitation to this study is that, although the authors attempted to control for factors such as hip muscle strength and balance through the screening protocol, proprioception, muscle performance, or muscle activation was not directly compared between the pass and fail groups. It is possible that the demands of the SLST are greater than those of the screening protocol used in this study and that differences between the pass and fail groups could be due to these factors.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study showed that ankle dorsiflexion ROM and foot posture were not different between healthy subjects that perform the SLST with and without MKD. Future work should investigate SLST performance in individuals with foot and ankle dysfunction, as it has been reported that MKD during the SLST is a risk factor for ankle injuries.\textsuperscript{11} Additionally, because the ease of use of the evidence-based SLST protocol makes it attractive to clinicians and researchers alike, further investigation into its kinematics, associated muscle activation patterns, and related muscle performance is warranted.

CONCLUSION

Among healthy individuals that passed and failed the SLST for MKD, there were no significant differences in clinical measures of weight bearing and non-weight bearing ankle dorsiflexion ROM or foot posture. These findings refute the possibility of a "bottom-up" approach to explaining increased MKD during the SLST in healthy individuals. Based on the results of this study, clinicians should not use the clinical SLST protocol to detect differences in the clinical characteristics of the foot and ankle. However, clinicians may continue using the clinical SLST protocol to assess function in individuals with non-arthritic hip pain regardless of their ankle dorsiflexion ROM or foot posture.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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Kinematic and Kinetic Predictors of Y-Balance Test Performance

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Keywords: preventative medicine, physical therapy, movement screening, balance

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Background
The Y-Balance Test (YBT) assesses dynamic stability and neuromuscular control of the lower extremity. Several authors have analyzed kinematic predictors of YBT performance with conflicting results, but the influence of kinetic factors is not well understood.

Purpose
To examine kinematic predictors of YBT performance and determine the joint kinetics which predict YBT performance.

Study Design
Cross-sectional study.

Methods
Thirty-one physically active individuals performed YBT trials on a force plate while whole body kinematics were recorded using a motion capture system. Sagittal, frontal, and transverse plane joint kinematics and joint moments were calculated at maximum reach in each YBT reach direction. Variables correlated with reach distances at the p < 0.2 level were entered into a stepwise linear regression.

Results
In the anterior direction, knee flexion and torso rotation (R²=0.458, p<0.001) and knee extensor and hip abductor moments (R²=0.461, p<0.001) were the best kinematic and kinetic predictors of reach distance. In the posterior medial direction, hip flexion, ankle dorsiflexion, and ankle rotation accounted for 45.8% of the variance in reach direction (p<0.001) while hip and knee extensor, and hip abductor moments explained 72.6% of the variance in reach distance (p<0.001). In the posterior lateral direction, hip flexion and pelvic rotation (R²=0.696, p<0.001) and hip extensor moments (R²=0.453, p=0.001) were the best kinematic and kinetic predictors of reach distance.

Conclusion
The ability to generate large hip and knee joint moments in the sagittal and frontal plane are critical for YBT performance.

Level of Evidence
3.

INTRODUCTION
Balance is a critical component of athletic performance and injury prevention, and deficits in dynamic balance have been linked with an increased risk of lower extremity injury.¹⁻³ Therefore, the assessment of reliable tests of dynamic balance, and knowledge of the factors which influence performance on these tests is essential for developing injury screening protocols and injury prevention training. The star excursion balance test (SEBT) is one widely used measure of dynamic balance.¹,4⁻⁶ The SEBT involves single-leg standing while reaching with the opposite limb in eight different directions. Reach distances in each direction are then normalized to leg length. The SEBT has high in-
terrer and test-retest reliability,7,8 and performance on the test is indicative of lower extremity injury risk.1–3 However, the time required to perform all eight reach directions may limit the practicality of using the SEBT in clinical settings. Additionally, reach scores in certain directions of the SEBT are highly correlated with one another and thus likely redundant.9

As a result, the Y-Balance test (YBT) was created as a streamlined assessment, which includes only the anterior (ANT), posteromedial (PM), and posterolateral (PL) reach directions from the SEBT. Similar to the SEBT, the YBT has excellent interrater and test-retest reliability,8 and also predicts risk of lower extremity injury. Plisky et al.2 found high school basketball players were nearly three times as likely to develop a lower extremity injury if there was a greater than 4 cm difference in anterior reach scores between right and left limbs. The same study also reported that players were three times more likely to become injured if the normalized right reach composite score was less than 94% of those with higher composite scores. Gonell et al.3 reported that male soccer players had nearly quadruple the risk of lower extremity injury if they had greater than a 4 cm difference in PM reach distance between legs. Their study also reported an increased risk of injury for players who had a lower composite score than the sample average. Finally, normalized PL reaches of less than 80% leg length have been linked to increased risk of sustaining lateral ankle sprains.10 Given the growing use of the YBT as a clinical tool, and its potential for injury risk screening, it is critical to understand factors related to performance on the test.

Several authors have evaluated kinematic predictors of performance on the reach directions of the YBT and reported mixed results. Fullam and colleagues11 reported moderate, but not statistically significant correlations between sagittal plane hip, knee, and ankle excursion and ANT reach distance. Robinson and Gribble6 reported that hip flexion was significantly correlated with reach distances in all three directions while knee flexion was significantly correlated with reach distances in the ANT direction. Finally, Kang et al.12 reported only ankle dorsiflexion and trunk extension as being significant predictors of ANT reach distances. Both Kang et al. and Robinson and Gribble reported hip flexion as being important for PL and PM reach.6,12 However, Kang et al.12 reported high reaches in the PL and PM directions were achieved using hip flexion and trunk bending while Robinson and Gribble6 reported greater reach distances were achieved using greater hip frontal and transverse plane rotations.

While kinematic predictors of YBT performance have been examined, kinetic predictors of performance are still unknown. The net joint moment an individual can produce at a given joint might influence YBT performance and have implications for correlating YBT scores to deficits in neuromuscular control or strength of the lower extremity. The net joint moments are also likely responsible for the kinematics observed during the screen. However, information regarding the kinetic predictors of performance on dynamic balance tests such as the YBT is limited and addressing this gap is critical for fully understanding the utility of dynamic balance assessments such as the YBT. Therefore, the purpose of this study was to examine kinetic predictors of YBT performance and determine the joint kinetics which predict YBT performance. Based on the previously reported kinematic predictors of YBT performance it was hypothesized that the sagittal plane hip extensor moments would be predictive of ANT, PM and PL reach, while frontal plane hip abductor moments would be predictive of PM and PL reach.

MATERIALS AND METHODS

PARTICIPANTS

A convenience sample of thirty-one healthy individuals (sex: 15 M, 16 F; age: 23.06 ± 7.03 years; mass: 59.05 ± 9.83 kg; height: 1.72 ± 0.91 m) participated in this cross-sectional study. Participants were volunteers from the campus community and were all moderate to highly trained athletes whose primary sport was running (8.6 ± 6.0 years running experience; 83.7 ± 30.1 kilometers per week). Inclusion criteria included being between the ages of 18 and 45, having no injury which disrupted physical activity in the previous six months, and no history of a lower extremity surgery. Participants were recruited from September 2018 through July 2019, with participation occurring in the same time frame. Prior to participation all participants provided written informed consent. All protocols in this study were approved by the Institutional Review Board at Montana State University.

PROTOCOL

Participants completed a warmup consisting of five minutes of treadmill running at a self-selected pace, followed by a self-selected dynamic stretching routine. They then performed two YBT trials on their dominant limb. Only the dominant limb was considered in this study as previous work has shown no difference in performance between dominant and nondominant limbs in the YBT.13–15 A visual guide for each YBT reach direction was taped on the ground and the subject stood barefoot with the stance foot in the center of this guide.2 Participants were instructed to reach as far as possible in the anterior direction first, followed by the posteromedial and posterolateral directions, and to tap their foot on the ground at the furthest reach (Figure 1). Participants were given approximately one-minute rest between trials. Prior to performing trials, participants received verbal instruction and visual demonstration of the YBT and were allowed two practice trials with corrective feedback.16 All reaches were performed along the taped outline on the floor, and two trials were completed and used for analysis.

Whole body kinematics were recorded using a 10-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz while ground reaction forces were simultaneously recorded from a force plate (AMTI, Watertown, MA) sampling at 1000 Hz. Retroreflective markers were placed on the seventh cervical vertebrae and on a headband, and placed bilaterally on the acromioclavicular joints, medial and lateral humeral epicondyles, styloid processes of the radius and ulna, anterior superior iliac spines, iliac crests, posterior superior iliac spines, lateral thigh, medial and lateral femoral epicondyles, lateral shank, medial and lateral malleoli, head of the 1st, 2nd and 5th
metatarsals, navicular tuberosities, and the posterior aspect of the heel. Additional tracking clusters of four markers on rigid plastic shells were placed on the lateral aspects of the thigh and shank segments. Following marker placement, a standing static calibration trial was performed after which the medial femoral epicondyle and malleoli markers were removed.

DATA ANALYSIS

Raw marker trajectories and ground reaction force data were exported to Visual 3D (C-Motion Inc., Germantown, Maryland, USA) where they were filtered using zero-lag, low pass, Butterworth filters with cutoff frequencies of 8 Hz. To avoid non-physiologic discontinuities in joint moment data, the ground reaction forces were filtered at the same cutoff frequency as the markers. Anatomic coordinate systems for the lower extremity were defined based on ISB recommendations. Joint angles were calculated as XYZ Cardan angles describing the movement of the distal segment relative to the proximal segment corresponding to flexion/extension, ab/adduction, and axial rotation. Trunk and pelvis angles were calculated using similar rotation sequences and expressed relative to the fixed laboratory coordinate system. Joint moments at the ankle, knee, and hip were calculated in each plane using standard Newton-Euler inverse dynamics. Joint moments were expressed as internal moments in the coordinate system of the proximal segment and were normalized to body mass.

The participant’s leg length was calculated using the distance between the ASIS and medial malleolus markers during the static trial. In each direction, reach distance of the participant was measured as the maximum distance between the 2nd metatarsal head markers on the reach limb and stance limb. Reach distances were then normalized to leg length. In each plane, kinematics and kinetics were evaluated at the maximum reach distance for each reach direction.

STATISTICAL ANALYSIS

Peak joint angles and moments at the hip, knee, and ankle, and peak torso and pelvis segment angles in all three planes of motion were calculated on each trial. The mean value for each variable across trials was used for further statistical analysis. Descriptive statistics of each of the above segments were calculated, and the normality of the distributions were analyzed using Kolmogorov–Smirnov tests. Pearson product correlations were analyzed for each kinematic and kinetic variable at peak reach for each reach direction. A stepwise linear regression was performed to determine which kinematic and kinetic variables were predictive of reach distance in each reach direction, with kinematic and kinetic variables each being considered in their own separate regression models. Variables were included in the stepwise regression model if they were correlated with reach distance at the \( p < 0.2 \) level. All statistics were performed using SPSS (IBM Corp, Armonk, NY).

RESULTS

Kolmogorov–Smirnov tests indicated all variables were normally distributed (all \( p > 0.05 \)). Participants’ raw reach scores in the ANT, PL, and PM directions were 0.674 ± 0.068 m, 0.823 ± 0.107 m, and 0.913 ± 0.108 m (mean ± SD), respectively while normalized reach scores were 74 ± 5.8%, 90.7 ± 10.9%, 100.6 ± 10.7% of leg length for the ANT, PL, and PM reach direction, respectively. The kinematics at peak reach distance in each direction of the YBT are shown in Table 1.

Table 2 shows Pearson Product correlations between kinematic variables and normalized reach distance. Hip and knee flexion, torso ipsilateral bending, and pelvis contralateral rotation were highly correlated with reach distance in all three directions.

Table 3 shows the final stepwise linear regression model for kinematic variables and normalized reach distance. A model containing knee flexion and torso contralateral rotation explained 45.8% of the variance in AP reach distances.
Initially, 20.9% (p<0.001) of the variance in ANT reach distance was explained by the knee extensor moment, and the combination of the hip extensor moment in the stepwise model explained 46.1% (p<0.001) of the variance in ANT reach distance. For the PM direction, the hip extensor moment and the combination of hip extensor moment and hip abductor moment accounted for 44.3% and 67.7% (p<0.001) of the variance in reach distance, respectively. Inclusion of the knee extensor moment increased the explanation of variance for reach distance to 72.6% (p<0.001). The final model for PL reach included only the hip extensor moment, which explained 35.6% (p=0.001) of the variance in PL reach distance.

**DISCUSSION**

The purpose of this study was to clarify kinematic predictors of YBT performance and determine the joint kinetics which predict YBT reach score in each of the three reach directions. The single best kinematic predictor of performance for ANT reach was knee flexion, and the addition of contralateral torso rotation increased the predictive capa-
Table 2: Correlation coefficients between kinematic variables and reach distance in the anterior (ANT), posteromedial (PM), and posterolateral (PL) reach directions.

<table>
<thead>
<tr>
<th>Reach Direction</th>
<th>ANT</th>
<th>PM</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal plane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torso</td>
<td>0.007</td>
<td>0.592*†</td>
<td>0.666*†</td>
</tr>
<tr>
<td>Pelvis</td>
<td>-0.013</td>
<td>0.210</td>
<td>0.091</td>
</tr>
<tr>
<td>Hip</td>
<td>0.294†</td>
<td>0.725*†</td>
<td>0.750*†</td>
</tr>
<tr>
<td>Knee</td>
<td>-0.537*†</td>
<td>-0.353†</td>
<td>-0.456*†</td>
</tr>
<tr>
<td>Ankle</td>
<td>0.189</td>
<td>-0.237†</td>
<td>0.280</td>
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<tr>
<td>Frontal plane</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Torso</td>
<td>-0.461*†</td>
<td>0.381*†</td>
<td>-0.509*†</td>
</tr>
<tr>
<td>Pelvis</td>
<td>-0.063</td>
<td>0.092</td>
<td>-0.583*†</td>
</tr>
<tr>
<td>Hip</td>
<td>-0.013</td>
<td>-0.024</td>
<td>-0.247†</td>
</tr>
<tr>
<td>Knee</td>
<td>0.064</td>
<td>0.082</td>
<td>0.383†</td>
</tr>
<tr>
<td>Ankle</td>
<td>-0.031</td>
<td>0.172</td>
<td>-0.386*†</td>
</tr>
<tr>
<td>Transverse plane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torso</td>
<td>-0.400*†</td>
<td>-0.391*†</td>
<td>0.065</td>
</tr>
<tr>
<td>Pelvis</td>
<td>-0.436*†</td>
<td>-0.548*†</td>
<td>0.379†</td>
</tr>
<tr>
<td>Hip</td>
<td>0.048</td>
<td>0.239†</td>
<td>-0.180</td>
</tr>
<tr>
<td>Knee</td>
<td>0.249</td>
<td>0.065</td>
<td>-0.069</td>
</tr>
<tr>
<td>Ankle</td>
<td>-0.082</td>
<td>0.259†</td>
<td>-0.458*†</td>
</tr>
</tbody>
</table>

* indicates significant correlation at the p < 0.05 level, † indicates inclusion in the stepwise linear regression (p < 0.2).

Table 3: The kinematic variables included in the final stepwise linear regression for predicting reach distance in the anterior (ANT), posterior-medial (PM), and posterior-lateral (PL) directions. $R^2$ and p values are for overall model.

<table>
<thead>
<tr>
<th>Direction</th>
<th>$R^2$</th>
<th>p value</th>
<th>Variables included in model</th>
<th>β</th>
<th>95% CI β</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANT</td>
<td>0.288</td>
<td>0.002</td>
<td>Knee flexion</td>
<td>-0.002</td>
<td>-0.003 – -0.001</td>
</tr>
<tr>
<td></td>
<td>0.458</td>
<td>&lt; 0.001</td>
<td>Knee flexion</td>
<td>-0.002</td>
<td>-0.002 – -0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torso contralateral rotation</td>
<td>-0.003</td>
<td>-0.005 – -0.001</td>
</tr>
<tr>
<td></td>
<td>0.526</td>
<td>&lt; 0.001</td>
<td>Hip flexion</td>
<td>0.006</td>
<td>0.004 – 0.008</td>
</tr>
<tr>
<td></td>
<td>0.693</td>
<td>&lt; 0.001</td>
<td>Hip flexion</td>
<td>0.007</td>
<td>0.005 – 0.008</td>
</tr>
<tr>
<td>PM</td>
<td>0.769</td>
<td>&lt; 0.001</td>
<td>Ankle dorsiflexion</td>
<td>-0.007</td>
<td>-0.011 – -0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hip flexion</td>
<td>0.007</td>
<td>0.005 – 0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ankle dorsiflexion</td>
<td>-0.007</td>
<td>-0.011 – -0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ankle external rotation</td>
<td>0.005</td>
<td>0.002 – 0.009</td>
</tr>
<tr>
<td>PL</td>
<td>0.563</td>
<td>&lt; 0.001</td>
<td>Hip flexion</td>
<td>0.006</td>
<td>0.004 – 0.009</td>
</tr>
<tr>
<td></td>
<td>0.696</td>
<td>&lt; 0.001</td>
<td>Hip flexion</td>
<td>0.006</td>
<td>0.005 – 0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pelvic contralateral rotation</td>
<td>0.004</td>
<td>0.002 – 0.006</td>
</tr>
</tbody>
</table>

bility of the model. Hip flexion was the single best kine-
matic predictor of both posterior reaches, and the addition
of ankle dorsiflexion and external rotation improved the PM
model, while the addition of contralateral pelvic rotation
improved the PL model. The hypothesis regarding which
joint moments would predict YBT reach scores, was par-
tially supported. ANT reach was best predicted by the com-
bination of the knee extensor and hip abductor moments.
While the hip extensor and abductor moments best pre-
dicted PM reach, and PL reach was best predicted by the hip
extensor moments

To date, four studies, including the present one, have
evaluated kinematic predictors of YBT performance, all re-
porting different results. Fullam and colleagues[11] reported
Table 4: Correlation coefficients between kinetic variables and reach distance in the anterior (ANT), posteromedial (PM), and posterolateral (PL) reach directions.

<table>
<thead>
<tr>
<th>Reach Direction</th>
<th>ANT</th>
<th>PM</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>-0.033</td>
<td>-0.666†</td>
<td>-0.580†</td>
</tr>
<tr>
<td>Knee</td>
<td>0.457†</td>
<td>-0.287†</td>
<td>0.007†</td>
</tr>
<tr>
<td>Ankle</td>
<td>-0.228</td>
<td>0.083</td>
<td>0.203</td>
</tr>
<tr>
<td>Frontal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>0.292†</td>
<td>0.577†</td>
<td>-0.062</td>
</tr>
<tr>
<td>Knee</td>
<td>-0.001</td>
<td>0.136</td>
<td>-0.244</td>
</tr>
<tr>
<td>Ankle</td>
<td>-0.228</td>
<td>-0.123</td>
<td>0.231</td>
</tr>
<tr>
<td>Transverse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>-0.044</td>
<td>0.319</td>
<td>0.271†</td>
</tr>
<tr>
<td>Knee</td>
<td>0.106</td>
<td>-0.604†</td>
<td>0.494†</td>
</tr>
<tr>
<td>Ankle</td>
<td>-0.354†</td>
<td>-0.070</td>
<td>0.122</td>
</tr>
</tbody>
</table>

* indicates significant correlation at the p<0.05 level, † indicates inclusion in the stepwise linear regression model.

Table 5: The kinetic variables included in the final stepwise linear regression for predicting reach distance in the anterior (ANT), posterior-medial (PM), and posterior-lateral (PL) directions. R² and p values are for overall model.

<table>
<thead>
<tr>
<th>Direction</th>
<th>R²</th>
<th>p value</th>
<th>Variables included in model</th>
<th>β</th>
<th>95% CI β</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANT</td>
<td>0.209</td>
<td>0.01</td>
<td>Knee extensor moment</td>
<td>0.044</td>
<td>0.12 - 0.077</td>
</tr>
<tr>
<td></td>
<td>0.461</td>
<td>&lt;.001</td>
<td>Knee extensor moment</td>
<td>0.064</td>
<td>0.035 - 0.094</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hip abductor moment</td>
<td>0.153</td>
<td>0.067 - 0.240</td>
</tr>
<tr>
<td></td>
<td>0.443</td>
<td>&lt;.001</td>
<td>Hip extensor moment</td>
<td>-0.147</td>
<td>-0.210 - -0.085</td>
</tr>
<tr>
<td></td>
<td>0.677</td>
<td>&lt;.001</td>
<td>Hip extensor moment</td>
<td>-0.131</td>
<td>-0.180 - -0.082</td>
</tr>
<tr>
<td></td>
<td>0.726</td>
<td>&lt;.001</td>
<td>Hip extensor moment</td>
<td>0.145</td>
<td>0.079 - 0.211</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hip abductor moment</td>
<td>-0.145</td>
<td>-0.191 - -0.096</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hip extensor moment</td>
<td>0.114</td>
<td>0.046 - 0.183</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Knee extensor moment</td>
<td>-0.056</td>
<td>-0.107 - -0.004</td>
</tr>
<tr>
<td>PM</td>
<td>0.336</td>
<td>.001</td>
<td>Hip extensor moment</td>
<td>-0.164</td>
<td>-0.251 - -0.076</td>
</tr>
</tbody>
</table>

ANT reach direction was moderately correlated with sagittal plane hip, knee, and ankle excursions, only one of which was included in our kinematic model. Kang et al.12 reported a kinematic model for ANT reach which included ankle dorsiflexion and trunk extension, neither of which were significant predictors in our kinematic model. Finally, Robinson and Gribble6 reported that peak hip and knee flexion predicted ANT reach distances, which is partially consistent with our results. The discrepancies in kinematic models for ANT reach distance could be explained by how the ANT reach was conducted. Specifically, Kang et al.12 did not allow participants to lift their heel during the YBT protocol while the current study did not include this limitation with the participants. The allowance of heel lift could reduce the importance of ankle dorsiflexion, while requiring the heel to maintain contact with the ground would emphasize ankle range of motion. That said, Robinson and Gribble6 also did not allow heel lift, and their final kinematic model did not include ankle dorsiflexion. The decision whether or not to allow heel lift is inconsistent across studies, but it is our suggestion that future studies on YBT should not allow heel lift, as plantar flexor strength and ankle ROM have been linked with performance on other balance tests.19,20 Requiring the heel to maintain contact with the ground may increase the ability of the YBT to detect deficits in plantar flexor strength, ankle ROM, and neuromuscular control, and should therefore be required across studies and clinical applications.

While there were some differences in variables included in the final models, the kinematic based prediction models for AP reach, both from previous studies6,12 and the current study, all rely heavily on sagittal plane motion. This high-
lights the necessity of large range of motion in the sagittal plane in order to perform the ANT reach of the YBT. However, such large ranges of motion require joint stability and how this stabilization happens may reflect individual strategies used to accomplish the AP reach. Robinson and Gribble suggest that the knee flexion ROM during the ANT reach of the YBT is an important variable in predicting YBT reach score. The amount of knee flexion that can be achieved is related to the magnitude of the knee extensor moment which can be generated. Indeed, the kinetic model for ANT reach showed that knee extensor moments at peak reach were one of the predictors of ANT reach distance. This finding, coupled with previous studies reporting increased EMG signals in the vasti muscles during the ANT reach suggest that the neuromuscular control and strength of the quadriceps muscle group may be crucial for ANT reach performance. Clinically, decreased ANT reach distance might be indicative of insufficient quadriceps function.

The final kinematic model for ANT reach also included contralateral torso rotation. The kinematic model reported by Kang et al. noted that trunk extension was an important predictor of ANT reach. Combined, these results suggest that counterbalanced trunk movement, whether obtained through extension or rotation, appears to be important for ANT reach performance. However, it is not possible to effectively rotate the trunk unless one can stabilize the pelvis. In support of this, the final kinetic model for ANT reach also included hip abductor moments as being a predictor of ANT reach distance. Several studies have reported that hip abductor muscle strength is correlated to ANT reach distance and that gluteus medius activity is highest during the ANT reach direction. Thus, clinically, in addition to poor quadriceps function, low ANT reach distances may be indicative of hip abductor insufficiencies. Differentiating between the two requires visualization of YBT performance, and not relying solely on reach distances. Specifically, it is recommended clinicians watch for any knee valgus or femoral internal rotation which may occur during performance of the YBT, as hip abductor weakness has been cited as a contributing factor to both knee valgus and femoral internal rotation.

In agreement with previous studies, the kinematic model for both posterior reach directions included hip flexion. The importance of being able to produce large ranges of hip flexion is supported by the kinetic models for posterior reach distances including hip extensor moments for both PM and PL reach, and by other studies which show hip extension strength is strongly correlated with posterior reach performance. However, Kang et al. also found that trunk bending away from the direction of reach explained additional variance in both PL and PM reach distances. In contrast, the final kinematic models did not involve any trunk kinematics. Rather, ankle dorsiflexion and rotation improved the PM model, while pelvic rotation improved the PL model. One possible explanation for this difference is the participants in the two studies. While the inclusion criteria were similar, the participants in Kang et al. were recreationally active while participants in the current study were moderately to highly trained runners. Thus, it is possible that participants in the current study had sufficient strength to produce the requisite hip extensor and abductor moments without requiring movement of the torso to counter-balance. While several studies have investigated the relationships between strength and YBT reach distances, to date no studies have reported whether strength influences the strategies individuals use to obtain those reach distances. This would seem to be an important area for future research, as clinically, observing the strategy an individual uses may provide insights into specific deficits in their strength or neuromuscular control.

In addition to hip extensor moments, including the hip abductor moment increased the variance explained by the kinetic model for PM reach. Previous authors have shown that hip abductor strength is correlated with both posterior reach directions. Hip abduction weakness has also been correlated with an increased risk of lower extremity injury. Thus, the ability of the YBT to predict risk of injury may be due the influence of hip extensor and abductor muscle coordination and strength on test performance. This has been suggested for other clinical movement screens such as the single leg drop jump where hip abductor strength is critical for resisting valgus loading of the knee. The YBT may predict injury risk through a similar mechanism. As such, clinically, the posterior reaches of the YBT may be especially useful for analysis of hip musculature dysfunction.

There are several limitations to consider when interpreting the results of this study. First, previous studies documenting the ability of YBT to predict injury have included multi-direction sports such as football, soccer, and basketball. However, participants in the current study were primarily runners, which is a more unidirectional sport. The inclusion of multidirectional athletes, recreationally active, or sedentary individuals may change the kinematic or kinetic predictors of YBT reach scores. Second, subjects performed the YBT barefoot since most prospective studies identifying a relationship between performance on the YBT and injury were done barefoot. It is possible that performance on the YBT, and the relationships observed in the current study, may be influenced either by wearing shoes, or by the type of shoe worn during testing. Third, participants included both males and females who were analyzed together. While some studies have reported differences in YBT reach distances between males and females, others have reported no differences in reach distances, but differences in the kinematics used to achieve a given reach distance. Thus, the relationships observed in the current study may be different if only males or only females were considered. Finally, many YBT studies are performed using the YBT test kit (Move2Perform, Evansville, IN), while this study did not utilize such a device. There may be differences in YBT reach distances between studies which measure reach with a device, and those that measure reach distance as the displacement between bilateral metatarsals. Future studies should evaluate the effects of footwear and performance method on YBT performance.

CONCLUSIONS

In summary, the results of this study indicate that kinematics of the ankle, knee, hip, and torso were all important for predicting YBT reach distances. The joint kinetics during the YBT also predicted performance on the test, most
notably, the knee extensor and hip abductor moment explained variance in ANT and PM reaches, while the hip extensor moment explained variance in PL and PM reaches. These results suggest that the ability to generate moments in the sagittal and frontal plane at the hip and knee is critical to YBT performance and may have implications for the ability of the YBT to identify injury risk.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

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REFERENCES


Original Research

Lower Extremity Kinematics of the Y-Balance Test in Healthy and ACL Injured Adolescent Females

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Keywords: anterior cruciate ligament, dynamic balance, functional testing, 2-dimensional video analysis, movement system

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Background
Adolescent females are at significant risk for sustaining an ACL injury. The Y-Balance Test (YBT) is frequently used to evaluate neuromuscular control and lower extremity function. However, few studies have quantified 2D lower extremity kinematics during performance of the YBT, and there is an absence of kinematic data specific to at-risk adolescent females.

Purpose
To examine lower extremity joint kinematics during execution of the YBT by healthy and ACL-injured adolescent females.

Study Design
Prospective cohort.

Methods
Twenty-five healthy and ten ACL-injured (mean time from injury 143 days) adolescent females were assessed using the YBT. Sagittal and frontal plane knee and ankle motion was video recorded during execution of the YBT anterior reach movement. Ankle dorsiflexion, knee flexion, and knee valgus angles were quantified via kinematic analysis. ANOVAs with a post hoc Bonferroni correction were used to compare YBT scoring (%LL) and kinematic data between groups. Pearson product-moment correlations determined the relationship between kinematic data and YBT scoring.

Results
Healthy and ACL-injured subjects demonstrated similar YBT scores and lower extremity kinematic data. Healthy subjects demonstrated a weak positive correlation between ankle dorsiflexion and YBT scoring, and a weak negative correlation between knee valgus and YBT scoring. These relationships did not exist for ACL-injured subjects. Kinematic data for both groups also demonstrated a large degree of variability, regardless of YBT score.

Conclusions
Adolescent females frequently utilize a variety of lower extremity movement strategies when performing a functional movement task, and scoring on the YBT offers limited insight regarding lower extremity joint kinematics and ACL-injury risk in a physically active adolescent female population.

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INTRODUCTION

The anterior cruciate ligament (ACL) is one of the most common sites of orthopedic injury, with an annual incidence of 68.6 per 100,000 person-years in the general population. While risk of ACL injury is significant for both sexes, adolescent females have a 1.6-fold greater rate of ACL injury per athletic exposure than adolescent males, with the peak incidence (227.6 per 100,000) of ACL injury occurring in girls 14-16 years of age. Research seeking to explain this gender disparity has frequently focused on modifiable biomechanical and neuromuscular factors that may influence lower extremity kinematics and the performance of functional movement tasks.

Functional movement testing that involves single-leg squats, lateral step-downs or various jump landing tasks suggests that dynamic knee valgus measures may be predictive of ACL injury. Initial investigations comparing sexes suggest that females demonstrate greater alterations in lower extremity kinematics, and deficits in dynamic balance and postural stability when performing the same movement tasks. Beyond this, the dynamic knee valgus angle has also been demonstrated to influence ankle joint kinematics. As such, further clinical research is needed to clarify the relationship between the knee valgus angle and lower extremity kinematics in an at-risk adolescent female population.

The Y-Balance Test (YBT) is a dynamic balance test that is frequently used in clinical and research settings to assess lower extremity function. Performance on this test is quantified as a measure of maximal reach distance in a specific direction, or as a calculated composite score (average distance of all reach directions). Dynamic balance testing is frequently used as a screening tool to identify individuals at risk of lower extremity injury; to assess deficiencies following injury; or to monitor rehabilitation progress. Lower test scores have previously been associated with an increased risk of ACL injury, and following ACL reconstruction. Neuromuscular education and balance training programs have been reported to improve scoring on dynamic balance tests such as the YBT.

However, few investigators have examined whether a link exists between kinematic joint measures for the lower extremity and performance on dynamic balance tests such as the YBT, and currently there is an absence of data which is specific to an at-risk adolescent female population.

The purpose of this investigation was to examine 2D lower extremity joint kinematics during execution of the YBT by healthy and ACL-injured adolescent females. The study had three specific aims: 1) Measure and compare the YBT reach distances for healthy and ACL injured adolescent females; 2) Measure and compare the ankle and knee joint angles of healthy and ACL injured adolescent females when performing the YBT anterior reach movement; and 3) Determine whether a relationship exists between lower extremity kinematic measures and scoring on the YBT anterior reach movement in healthy and ACL injured adolescent females.

METHODS

PARTICIPANTS

Following institutional ethics approval (H2014:302), healthy and ACL-injured adolescent females were recruited from the community to participate in this clinical study. Twenty-five healthy adolescent females and an exploratory group of 10 ACL-injured adolescent females consented to participate. Healthy subjects reported no recent trauma to the lower extremity; subjects in the ACL-injured group had their injury confirmed via orthopaedic consult and magnetic resonance imaging. All participants completed a standardized screening protocol which indicated that they had no knee joint effusion, were able to fully flex and extend the knee joint through a full range of motion, had no quadriceps lag with an active straight-leg raise, had quadriceps strength of at least 75% of the unaffected leg and were able to perform 10 consecutive single-legged hops pain free.

All participants were female, 12-18 years of age, with no history of lower extremity injury (other than ACL trauma in the injured group) or concussion in the prior six months. The height, weight, and BMI of all subjects were recorded. Knee joint laxity for all subjects was evaluated using the KT-1000 (MEDmetric Corp., San Diego, CA). Maturation status was determined using the self-reported pubertal maturation observational scale (PMOS); leg dominance was determined by preference for kicking a ball; and information regarding sport participation for each participant was documented.

YBT TESTING FOR DYNAMIC BALANCE

All subjects completed the YBT (Move2Perform, Evansville, IL) according to previously described and standardized procedures. Following completion of the practice trials, the distance from the YBT apex of the most proximal edge of the reach indicator was recorded for the first test trial while participants performed movements in three directions: anterior (ANT), posterioromedial (PM) and posterolateral (PL). The dominant (or ACL deficient) limb served as the support leg. All reach distances were normalized as a percentage of each participant’s stance-limb length (%LL), and measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine lying position.

KINEMATIC ANALYSIS OF LOWER EXTREMITY JOINT ANGLES

For the purpose of this investigation, only the YBT anterior (ANT) reach direction was recorded and used for kinematic analysis. Previous research suggests that this reach direction served as a significant discriminator in predicting risk of lower extremity injury, and pilot testing revealed that kinematic data from the ANT reach direction demon-
strated the greatest accuracy. Two HD video cameras (Sony Handycam HDR-UX20, Sony Corp., Minato, Tokyo, Japan) were used to collect lower extremity kinematic data while each participant performed the YBT in the ANT direction. One camera was positioned three meters in front of each subject to capture a full frontal-plane view, while the other camera was positioned three meters lateral to each subject to capture a sagittal view. All digital images were coded and saved for subsequent video analysis. Analysis was only completed for the dominant limb of the healthy subjects and the injured limb of the ACL-injured participants.32,33

Open-license video analysis software (Kinovea 0.8.15) was then used to quantify three joint angles at the point of maximal ANT reach distance when performing the YBT: (1) the degree of knee joint flexion in the sagittal plane; (2) the degree of ankle joint dorsiflexion in the sagittal plane; (3) the knee valgus angle in the frontal plane. The same anatomical landmarks were used as reference points for calculating the joint angles of all participants. Selection of these landmarks was based on methodologies previously described in the literature.34–36 Each kinematic measure was calculated using the Kinovea software (Figure 1A & B). The angle of knee flexion in the sagittal plane was determined by measuring the angle created between the lower leg and the posterior thigh with the neutral or starting angle being considered full extension (180°). The angle of ankle dorsiflexion in the sagittal plane was determined by measuring the angle created between the long axis of the foot and the lower leg with neutral being considered 90° of dorsiflexion while in a standing position. The angle of knee valgus in the frontal plane was determined by measuring the angle created between the lateral thigh and the lower leg with neutral being considered full extension (180°). This orientation allowed the knee valgus angle to be reported as a positive value.

STATISTICAL ANALYSIS

A power analysis (n=2{(1.96+0.84)6.7/8}2) from a previous study of healthy recreationally active adolescent females performing the ANT reach of the YBT indicated that a minimum of 12 healthy subjects would be required to adequately power this investigation.36 ANOVA testing was used to analyze for differences between the healthy and ACL-injured subjects on demographic, anthropometric, YBT reach distances and the lower extremity joint angles. An alpha level of p < 0.05 was set to determine statistical significance. The relationship between kinematic angles and the YBT scoring was evaluated using Pearson product-moment correlations.26,37,38 Correlation coefficients (r) of 0.25-0.49, 0.50-0.74, and 0.75-1.0 were considered to represent weak, moderate and strong relationships.39 The 95% confidence interval (CI) for the YBT reach distances of the healthy subjects was used to group subjects for comparison. ANOVA testing between groups with a post hoc Bonferroni correction of p < 0.0167 were used to determine statistical significance. In addition, we performed single-subject analysis for each variable using the healthy subject 95% CI’s for comparison.

RESULTS

Results indicated that the ACL-injured group was significantly older than the healthy group (Healthy: 14.0±1.3 yrs; ACL injured: 16.3±1.6 yrs, p < 0.001). With the ex-
Table 1: Y-Balance Test (YBT) reach distances for all participants [mean ± SD, (95% CI)]

<table>
<thead>
<tr>
<th>YBT Reach Direction</th>
<th>Healthy (n=25)</th>
<th>ACL-Injured (n=10)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior (ANT) (%LL)</td>
<td>65.1 ± 6.0 (62.6 - 67.6)</td>
<td>64.5 ± 5.9 (60.3 - 68.7)</td>
<td>0.80</td>
</tr>
<tr>
<td>Posteroomedial (PM) (%LL)</td>
<td>99.3 ± 7.5 (96.2 - 102.4)</td>
<td>96.0 ± 9.5 (89.2 - 102.8)</td>
<td>0.30</td>
</tr>
<tr>
<td>Posteralateral (PL) (%LL)</td>
<td>97.7 ± 9.0 (94.0 - 101.4)</td>
<td>95.1 ± 8.4 (89.1 - 101.1)</td>
<td>0.40</td>
</tr>
</tbody>
</table>

%LL – Percentage of limb length

Table 2: Lower extremity kinematic data for all participants when performing the YBT anterior reach movement [mean ± SD, (95% CI)]

<table>
<thead>
<tr>
<th></th>
<th>Healthy (n=25)</th>
<th>ACL-Injured (n=10)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion angle (degrees)</td>
<td>66.4 ± 10.9 (61.9 - 70.9)</td>
<td>70.9 ± 9.2 (64.3 - 77.5)</td>
<td>0.25</td>
</tr>
<tr>
<td>Ankle dorsiflexion angle (degrees)</td>
<td>28.4 ± 4.6 (26.5 - 30.3)</td>
<td>27.2 ± 4.9 (23.7 - 30.7)</td>
<td>0.49</td>
</tr>
<tr>
<td>Knee valgus angle (degrees)</td>
<td>3.9 ± 6.4 (1.3 - 6.5)</td>
<td>5.2 ± 7.8 (-0.4 - 10.9)</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Table 3: Relationship between YBT anterior reach scores and lower extremity kinematic data

<table>
<thead>
<tr>
<th></th>
<th>Healthy (n=25)</th>
<th>ACL-Injured (n=10)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion angle (degrees)</td>
<td>0.37</td>
<td>0.43</td>
<td>0.21</td>
</tr>
<tr>
<td>Ankle dorsiflexion angle (degrees)</td>
<td>0.42*</td>
<td>0.06</td>
<td>0.87</td>
</tr>
<tr>
<td>Knee valgus angle (degrees)</td>
<td>-0.40*</td>
<td>0.30</td>
<td>0.52</td>
</tr>
</tbody>
</table>

* p < 0.05

ception of knee joint laxity (Healthy: 6.5±2.6 mm; ACL-injured: 11.7±1.7 mm, p < 0.001), there were no significant differences between the anthropometric measurements of the two groups. All participants had a healthy BMI (Healthy: 22.5±4.8 kg/m²; ACL injured: 24.8± 4.6 kg/m², p=0.18), and were predominantly post-pubertal adolescents (Healthy: 68%; ACL injured: 60%) who participated in a variety of recreational sporting activities including basketball, volleyball, soccer, hockey, and dance. For ACL-injured participants, the mean time from injury to the baseline examination for this study was 143 days (range: 24-365).

YBT reach distances and lower extremity kinematic data for all subjects (organized by group) are presented in Tables 1 and 2. There were no significant differences in YBT reach distances or lower extremity kinematic data when comparing healthy and ACL-injured groups.

Table 3 illustrates the relationship between the YBT ANT reach distance and lower extremity joint angles. Pearson correlation coefficient testing for the healthy subjects suggested that there were weak relationships (0.25-0.49) between the YBT ANT reach distance and the degree of ankle dorsiflexion (positive), the degree of knee valgus (negative), and that there was a trend towards a positive relationship with the degree of knee flexion. These relationships were only significant for the ankle dorsiflexion and knee valgus angles. Analysis of data for the ACL-injured group suggested that there were no relationships between lower extremity joint angles and YBT ANT reach scores.

Using YBT ANT reach data, 95% confidence intervals (CI) were calculated for each group. Subjects were then stratified into three groups: (1) Above 95% CI = 72.5 ± 2.8 %; (2) Within 95% CI = 64.7 ± 1.5 %; and (3) Below 95% CI = 58.2 ± 3.3 %. A comparison of the kinematic data across the three groups indicated that there were no significant differences for either the healthy participants or the ACL injured participants (Table 4).

These same three YBT ANT reach distance groupings (above, within or below 95% CI) where then used to perform single-subject analyses. Data illustrated that there was little consistency in the movement patterns demonstrated about the ankle and knee joints by either the healthy or ACL-injured subjects when performing the ANT reach of the
Table 4: Kinematic data (mean ± SD) for healthy and ACL-injured participants categorized by YBT anterior reach distance

<table>
<thead>
<tr>
<th></th>
<th>Healthy</th>
<th>ACL-injured</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Above 95% CI (n=7)</td>
<td>Above 95% CI (n=2)</td>
</tr>
<tr>
<td>Knee flexion angle</td>
<td>70.3 ± 15.0</td>
<td>81.0 ± 8.5</td>
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<tr>
<td>(degrees)</td>
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<tr>
<td>Ankle dorsiflexion</td>
<td>30.0 ± 3.5</td>
<td>32.0 ± 1.4</td>
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<tr>
<td>angle (degrees)</td>
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<tr>
<td>Knee valgus angle</td>
<td>2.6 ± 8.9</td>
<td>6.0 ± 14.1</td>
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<tr>
<td>(degrees)</td>
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<td></td>
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<tr>
<td>Within 95% CI (n=11)</td>
<td>68.6 ± 6.3</td>
<td>69.8 ± 5.7</td>
</tr>
<tr>
<td>Below 95% CI (n=7)</td>
<td>58.9 ± 9.6</td>
<td>67.0 ± 10.2</td>
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<tr>
<td></td>
<td>Within 95% CI (n=4)</td>
<td>Within 95% CI (n=4)</td>
</tr>
<tr>
<td>Knee flexion angle</td>
<td>29.5 ± 3.0</td>
<td>22.8 ± 4.6</td>
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<tr>
<td>(degrees)</td>
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<td></td>
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<tr>
<td>Ankle dorsiflexion</td>
<td>3.5 ± 6.1</td>
<td>5.5 ± 8.5</td>
</tr>
<tr>
<td>angle (degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee valgus angle</td>
<td>25.1 ± 6.4</td>
<td>29.3 ± 2.1</td>
</tr>
<tr>
<td>(degrees)</td>
<td></td>
<td></td>
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<tr>
<td>Below 95% CI (n=4)</td>
<td>5.9 ± 3.8</td>
<td>4.5 ± 6.4</td>
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</tbody>
</table>

Table 5: Single subject categorical comparison of kinematic data and YBT anterior reach distance for healthy participants

<table>
<thead>
<tr>
<th>YBT</th>
<th>Knee flexion angle</th>
<th>Ankle dorsiflexion angle</th>
<th>Knee valgus angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above 95% CI</td>
<td>+</td>
<td>0</td>
<td>-</td>
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<tr>
<td></td>
<td>+</td>
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<tr>
<td>Within 95% CI</td>
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<tr>
<td>Below 95% CI</td>
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Legend: + above 95% CI; 0 within 95% CI; and – below 95% CI

DISCUSSION

This is one of the first investigations to examine lower extremity kinematics during performance of the YBT in both at-risk healthy and ACL-injured adolescent females. Results suggested that there were no significant differences between the healthy and ACL-injured subjects on YBT scoring, or the lower extremity joint angles observed when partic-
Table 6: Single subject categorical comparison of kinematic data and YBT anterior reach distance for ACL-injured participants.

<table>
<thead>
<tr>
<th></th>
<th>YBT</th>
<th>Knee flexion angle</th>
<th>Ankle dorsiflexion angle</th>
<th>Knee valgus angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above 95% CI</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Within 95% CI</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
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<tr>
<td></td>
<td>-</td>
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<td>0</td>
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<tr>
<td>Below 95% CI</td>
<td>0</td>
<td>0</td>
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</table>

Legend: + above 95% CI; 0 within 95% CI; and – below 95% CI

Participants performed the YBT ANT reach direction. Data for the healthy adolescents indicated that there were only weak correlations between scoring on the YBT and the angle of ankle dorsiflexion (larger YBT scores were associated with a greater degree of ankle dorsiflexion) and the angle of knee valgus (larger YBT scores were associated with less knee valgus), but there was little relationship between the angle of knee flexion and YBT ANT reach scoring. Results for the ACL-injured group suggested there were no relationships between any of the lower extremity kinematic measures and ANT reach scoring on the YBT. Interestingly, a comparison of subjects when grouped by their performance on the YBT ANT reach (above, within or below the 95% CI) also failed to identify any consistencies between YBT scoring and lower extremity joint angles (for example: a girl who scored well on the YBT was just as likely to have a large knee flexion angle as a girl who performed poorly). A similar result was observed when single-subject analysis was performed. These findings serve to reinforce the notion that adolescent females frequently utilize a variety of lower extremity movement strategies when performing functional movement tasks typically observed in sport, and suggest that ANT reach scoring on the YBT may offer limited insight regarding lower extremity joint kinematics, and ACL-injury risk in a physically active adolescent female population.

This investigation is among the first to report both dynamic balance and kinematic data that is specific to both a healthy and ACL injured adolescent female population who participate in a variety of recreational sporting activities and is nearing or has recently reached physical maturation. While data indicated that the healthy group was much younger than the ACL injured group, the only significant difference observed in the anthropometry of the two groups was on the parameter of knee joint laxity (ACL deficient group > healthy group). As such, the results help to fill a significant void that currently exists within the biomechanical and neuromuscular testing literature, and provides important baseline data that is generalizable to a much larger population of adolescent females that is at significant risk for ACL injury during sports participation.

The results serve to extend the findings of previous investigations on dynamic balance which have focused on athletes from specific sports,6,20 older age groups,40–42 or competitive sport.22,45 The literature indicates that dynamic balance scoring can vary greatly, and can be influenced by a host of factors including testing methodologies,26,58 the precision of the value reported,40,44–48 and the study’s population, age,40–42 sex,6,20,46,48,49 sport,6,20 and competitive level.22,45,50 YBT scoring for our healthy adolescent female population fell within the range of expected scores based on participants age, gender and competitive level – scores were slightly higher than those previously reported for adults;26,27,58 slightly lower than adolescent athlete scoring reported for both sexes;43,51 and most similar to scoring from older female participants.52,53 Normal function of the proprioceptive, vestibular, and visual systems are all important for dynamic balance, and each of these systems are still maturing and developing during the adolescent period.44,54–56 As such, it is possible that gender and biological changes associated with aging and physical maturation had a significant effect on YBT scoring in the present study;53,57 and caution should be used when comparing these data with previous reports for an adult population.

Kinematic data from the current investigation provides important information about lower extremity joint movements during the execution of the YBT ANT reach by a population of healthy adolescent females at significant risk for lower extremity injury. Sagittal plane data for the angle of ankle dorsiflexion25–27 and the angle of knee flexion25,25–27,58 were comparable to previous reports involving dynamic balance testing. Within a general population, dorsiflexion angles typically range from 32° to 39°, and knee flexion angles have been reported to range from 51° to 68°.25,25–27,58 To date, only one previous investigation has examined the knee valgus angle (mean=14.15±4.83) during performance of the YBT, and this study involved a physically mature population of co-ed university students (mean age of 22.7±2.2 years).27 Participant knee valgus angle for our adolescent female participants were significantly lower.
than values reported in this earlier study, and are much closer to values reported in another study which evaluated a single leg squat task in 30 physically active young females.9

This investigation also examined YBT ANT reach distance and lower extremity kinematics in an exploratory group of ACL-injured participants. Data indicated that YBT reach distance and joint angles were not significantly different when comparing healthy and ACL-injured adolescent females. These findings may suggest that our ACL-injured subjects were able to use some form of neuromuscular control in order to compensate for their ligamentous instability in their knee. Previous research does suggest that a percentage of ACL injured patients, often referred to as "copers", are capable of coordinating muscle activity to dynamically stabilize the knee and resume preinjury activities without episodes of the knee giving-way.59 Having said this, the current investigation of the YBT is the first to include ACL-injured adolescent individuals. Previous investigations of clinical dynamic balance using subjects with ACL injury have used less reliable dynamic balance testing protocols such as the Star Excursion Balance Test (SEBT).5,33 These studies found differences between the healthy controls and the ACL injured participants for the anterior reach direction.8 Although the YBT and SEBT testing protocols are similar, research suggests that the anterior reach distance performance and kinematic profiles of test subjects are different, and that each test imposes different neuromuscular demands and postural-control strategies on the partici- pant.26,38,60 Thus caution should be used when comparing results from the different forms of dynamic balance testing, and further neuromuscular research which targets ACL-injured subjects is required in order to clarify inconsistencies, and determine whether a difference really exists between injured and healthy limbs during execution of the YBT.8,33

Research on an adult population has previously indicated that the angle of ankle dorsiflexion is the best single kinematic predictor of YBT scoring in the anterior reach direction.27,61 Anterior reach YBT scores have also been reported to have a moderate correlation with the angle of knee flexion. But, no significant relationship has been established between YBT scoring and the angle of knee valgus.27 Results for a healthy adolescent female population were in agreement with the results of these earlier investigations, and suggested that a positive weak correlation existed between YBT scoring and the angle of ankle dorsiflexion (ie. subjects who achieved greater ankle dorsiflexion tended to be able reach further on the YBT). However, in contrast to these earlier reports data from this investigation suggested that there was no correlation between the angle of knee flexion and YBT anterior reach scoring, and that a negative correlation existed between a subject’s knee valgus angle and their YBT score (ie. as the angle of knee valgus increased, a subjects YBT anterior reach distance actually decreased). Previous research specific to an adolescent female population has suggested that kinematic assessment of the knee joint may be more important than the ankle joint as females demonstrate a larger dynamic knee valgus position than males when performing functional tasks such as jump landing and single leg squats.62–64 Dynamic knee valgus measures during the execution of functional tasks (such as the YBT) are reported to be predictive of risk for ACL injury in adolescent females.4,5,7,12 Results from this investigation are in agreement with other reports which suggest that lower YBT scores19–22 and greater knee valgus angles5,7,12 are frequently observed in populations who are at increased risk of ACL injury.

In contrast to the healthy subjects, data for the ACL-injured participants suggested that there was no relationship between lower extremity joint angles and YBT anterior reach scoring. While the large range in scoring and small sample size may have contributed to this finding, it is also possible that anterior/posterior joint instability and participant movement apprehension associated with ACL deficiency resulted in participants being more hesitant or guarded when performing the YBT anterior reach movement.65 As a result, the ACL injured subjects may have subconsciously utilized movement strategies the involved greater range of motion at the hip joint or within the trunk region to achieve similar reach distances while minimizing movements about their injured knee.23

Finally, a comparison of the kinematic data between the healthy and ACL-injured groups suggested that there were no significant differences in ankle and knee joint angles when performing the YBT ANT reach direction. These results were confirmed when data was organized by YBT confidence intervals and by single-subject analysis. The sensorimotor system that regulates balance and postural awareness relies on information from the visual, vestibular and somatosensory subsystems.56 However, pubertal growth is reported to inhibit the sensorimotor functions of the lower extremity and lead to awkward movement patterns.56 The variability of movement strategies we observed may be attributed to the fact that our participants were still progressing through or recently completed the maturation process, and as such their neuromuscular control and intersegmental limb coordination were still developing.56 During execution of the YBT, the only instructions given to subjects were to push the reach indicator as far as possible along the pipe in the reach direction while maintaining a unilateral stance with their hands on hips. No tips on how to enhance performance were given.16,46 Kinematic data for individual subjects would seem to suggest that adolescent females use a variety of movement strategies to achieve maximal reach distance, including ankle dorsiflexion, knee flexion and knee valgus. Standardized placement of the hands on hips was used to minimize the influence of upper body/extremity sway, although variations in hip and trunk movement were unavoidable. Balance-correcting strategies of the trunk and hip are often used to maintain one’s center of mass over a base of support and prevent loss of balance during a lower limb reach.25,27 Other investigations indicate that a similar anterior reach distance can be achieved by either flexing the hip and knee of the stance limb, or creating a Trendelenburg position, adducting the hip of the stance limb to lengthen the reach limb.25 Lack of stability at the trunk and hip is suggested to contribute to lateral trunk and Trendelenburg positions, and subsequently a knee valgus position.4,5,7 Unfortunately in this study, hip and trunk kinematic data were unable to be collected because the video cameras were positioned to collect information exclusive to the lower extremity. The specific influence of trunk and pelvic positions on the kinematics of
the lower extremity may reveal more information about the role of distinct or varied positional stabilization strategies during execution of the YBT, and should be examined in future investigations.

This study is not without limitation. The use of 2D video analysis restricted kinematic analysis to only the anterior reach direction of the YBT. Kinematic analysis of posterolateral & posteromedial reach directions are much more complex (due to the additional rotational movements of the trunk and lower extremity), and thus required more sophisticated 3D motion-capture equipment that was beyond the scope of this investigation. Additionally, due to time and lab space constraints in our data collection protocol (eg. multiple participants were being simultaneously evaluated) videotaping was restricted to only the first test trial for each subject. As such, it is possible that subjects may have altered their kinematic approach to performing the YBT over the three consecutive trials of the testing methodology. Kinematic analysis of each of these individual trials may have helped to provide a more reliable depiction of the relationship between lower extremity joint position and scoring on the YBT.

CONCLUSION

The results of this investigation indicate that there were no significant differences in YBT scoring and lower extremity kinematic data in the anterior reach direction when comparing the movement patterns of healthy and ACL-injured adolescent females. Additionally, both groups utilized a variety of lower extremity movement strategies when performing the functional movement task. Reach scoring on the YBT may offer limited insight regarding lower extremity joint kinematics, and ACL-injury risk in a physically active adolescent female population. Although beyond the scope of this study, results from future prospective, longitudinal investigations of both healthy and ACL-injured adolescent females could be used to identify the physical and neurological parameters that influence knee joint motion in this at-risk sporting population.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

Submitted: May 29, 2020 CDT, Accepted: November 08, 2020 CDT
REFERENCES


Background

Hop tests are commonly employed to evaluate functional limb symmetry after anterior cruciate ligament reconstruction (ACLR).

Purpose

To investigate the ability of eight hop tests to identify functional limb asymmetry in patients after ACLR.

Study Design

Prospective cohort.

Methods

Fifty patients were assessed 9-12 months following ACLR. Functional performance on both the operated and non-operated limb was assessed via eight hop tests, assessed in a randomised order. These included the: single (SHD), triple (THD) and triple crossover (TCHD) hop for distance, 6m timed hop (6MTH), single medial (MHD) and single lateral (LHD) hop for distance, single countermovement jump (SLCMJ) and timed speedy hop (TSHT). Differences in Limb Symmetry Indices (LSIs) across hop tests were compared, while Pearson’s correlations were undertaken to investigate the significance and strength of the association between hop test LSIs.

Results

Significant differences were observed across hop LSIs (p<0.0001). Mean LSIs for the SHD (95.0%), 6MTH (95.0%), THD (96.1%) and TCHD (95.3%) were ≥90% and significantly greater (p<0.05) than the MHD (87.3%), LHD (87.5%), SLCMJ (83.4%) and TSHT (86.5%), which were all <90%. The LSI for the SLCMJ was significantly lower (p<0.05) than all other hop tests. While significant correlations existed across the majority of hop LSIs, the strongest correlations existed between the SHD, THD and TCHD (r=0.70-0.80), and lowest correlations between the TSHT and the other hop tests (r=0.26-0.49).

Conclusions

The LHD, MHD and TSHT, as well as the SLCMJ in particular, were best able to demonstrate functional limb asymmetry in patients following ACLR. These hop measures should be incorporated into hop test batteries, if the purpose is to detect the presence of lingering functional deficits.

Level of Evidence

Level 3.
INTRODUCTION

While approximately 90% of patients that experience an anterior cruciate ligament (ACL) tear undergo ACL reconstruction (ACLR),1 Ardern et al. reported that only 65% of patients return to their pre-injury level of sport.2 Overall, following ACLR it has been reported that approximately 7% may sustain an ipsilateral re-tear and a further 8% a contralateral ACL tear,3,4 with young athletes (<25 years) that return to sport (RTS) demonstrating a combined secondary ACL injury rate of 23%.5 While a range of factors may contribute to ACL re-tears,1,5,6 the patient’s inability to regain muscle function and strength, both critical elements required in the safe RTS, have also been reported as key risk factors for re-tear.7,8 Consequently, physical performance testing is widely used in clinical settings to assess lower limb strength and functional symmetry, and research has demonstrated an increased re-injury risk if patients RTS without meeting certain strength and hop test performance cut-offs.9,10

Functional hop tests have been commonly employed in the assessment of patients after ACLR,9–11 often reported via a Limb Symmetry Index (LSI). The LSI is a measure of the operated limb as a percentage of the non-operated limb, and literature has suggested that an LSI >90% is considered to be ‘normal’ when comparing the ACLR limb to the non-operated limb.12,13 While LSIs are commonly employed to present functional outcomes,13–15 it is unknown how applicable this reported 90% cut-off is to different hop tests, while it has been reported that LSIs can overestimate knee function in patients following ACLR, particularly given de-conditioning that can occur in the comparative, non-operated limb.16 Despite their widespread use, many of these single limb hop tests are straight line movements and have been criticized for not sufficiently evaluating functional performance in patients following ACLR, particularly with a recent study suggesting some hop tests may be more sensitive in detecting side-to-side differences in functional performance.18 Nonetheless, these distance- and time-based performance hop tests remain a convenient and inexpensive means of assessing higher-level functional ability, are practical in a clinical setting without excessive space nor equipment required, and provide a quantifiable measure that can be assessed over time. Of course, the decision to progress rehabilitation, increase training loads and return to agility and/or sport-specific training (and eventually sport) is dependent on more than hop testing (and a hop test battery), including measures of isokinetic muscle strength assessment, physical fitness and biomechanical movement, as well as psychological readiness. However, an investigation into the array of hop tests is warranted to determine which may be a better reflection of function (and functional deficit) in patients following ACLR. While a battery of hop measures (rather than a single hop test) is recommended in the evaluation of patients after ACLR,19 the therapist must be confident that the hop tests they include in such a battery are able to assess higher level functional capacity, especially if their combined purpose is to detect the presence of lingering functional deficits.

Therefore, the primary purpose of the current study was to investigate the ability of eight hop tests to identify functional limb asymmetry in patients after ACLR. Firstly, it was hypothesized that significant variation in lower limb symmetry measures would exist across the eight functional hop tests employed, and those incorporating multi-directional movement would demonstrate greater asymmetry. Secondly, it was hypothesized that the strongest correlations between hop tests would exist for forwards distance-based hop measures, with the weakest correlations observed in those incorporating multi-directional movement.

METHODS

PARTICIPANTS

This cross-sectional study was undertaken in a consecutive series of 50 patients (34 males, 16 females) who had undergone primary ACLR, undertaken by one of five consultant orthopaedic surgeons within the private hospital system (each with >10 years of experience undertaking ACLR as a private consulting surgeon). Patients were assessed between January and August 2019, and were included if they were: 1) 16–50 years of age, 2) 9–12 months post-surgery, 3) had undergone ACLR utilising a hamstring autograft harvested from the ipsilateral knee, 4) were experiencing no ongoing problems with either the operated or non-operated knee (inclusive of both pain and/or perceived function during their own activities of daily living), 5) did not report any other musculoskeletal concerns with pain, symptoms and/or dysfunction in the ipsilateral or contralateral limb (that would affect their ability to perform in the hop measures), 6) had no prior recollection of significant injury or surgery on the non-operated (contralateral) limb, and 7) had returned (or were planning on returning) to Level 1 (participation 4-7 days/week) or Level 2 (participation 1-3 days per week) sports that included jumping, hard pivoting, cutting, running, twisting and/or turning sports, as reported by the Noyes Sports Activity Rating Score (NSARS).20 The cohort included 42 (84%) and 8 (16%) patients that ruptured their ACL in a non-contact and contact situation, respectively. Patients undergoing concomitant meniscectomy (n=10) or meniscal repair (n=14) were included.

FUNCTIONAL HOP TEST BATTERY

Patients underwent a standardized warm up, consisting of five minutes at low resistance on an upright stationary bike at a self-determined intensity, followed by an optional stretching period of 5–10 minutes which was not standardized and dictated by the patients preferred warm up routine. Patients then completed eight functional hop tests (two timed and six distance/height hop tests), undertaken in a pre-determined randomized order. Patients were given verbal descriptions of each hop test prior to undertaking each and were initially permitted two to three warm-up hops on each limb prior to initiating the hop battery. Each test was initiated on the non-operated limb, alternating between the non-operated and operated limbs until the designated number of valid test trials were obtained for each. While the hop battery was randomized in an attempt to mitigate any fatigue affects over time, the rest period between the hop trials was not standardized and was dictated by the patient’s perceived readiness to proceed (that is, rather than
setting a pre-determined rest period within each hop trial, an attempt to ‘standardize’ for each patient was made by ensuring that the patient could proceed when they deemed ready).

The eight functional hop tests included the: 1) Single Hop for Distance (SHD), 2) 6m Timed Hop (6MTH), 3) Triple Hop for Distance (THD), 4) Triple Crossover Hop for Distance (TCHD), 5) Single Medial Hop for Distance (MHD), 6) Single Lateral Hop for Distance (LHD), 7) Single Limb Countermovement Jump for Height (SLCMJ), and 8) Timed Speedy Hop Test (TSHT). For the SHD, patients were advised to hop off one limb as far as possible (forwards), landing on the same limb in a controlled manner (for this study, a controlled landing was defined as the patient’s ability to cleanly hold or ‘stick’ the landing without any observed shuffle or stutter, and without touching down with the contralateral limb or any other part of the body) (Figure 1). The 6MTH involved multiple consecutive single limb hops on the same limb over a distance of 6m (Figure 2). A stopwatch was used to determine the time taken to cover the distance, and the patient was instructed to hop over the designated distance in as little time as possible, treating the 6m mark as a finish line without the need to land in a controlled manner. For the THD, patients had to perform three consecutive hops for maximum distance in a forward direction (all on the same limb, and without pausing in between each hop with the exception of the final landing), with a controlled landing on the third and final hop (Figure 3). For the TCHD, similar to the THD patients had to perform three consecutive hops for maximum distance, though crossing back and forth over a custom-made 15cm width mat, without touching the mat (Figure 4). For both the SHD, THD and TCHD, the trial was considered successful if the patient landed in a controlled manner on the final hop.

For the MHD (Figure 5) and LHD (Figure 6), patients were instructed to hop sideways in a medial or lateral direction, respectively, as far as possible. The hop was again considered successful if the patient landed in a controlled manner, though with the foot landing parallel to its starting position. For the SLCMJ, patients were asked to hop off one leg as high as possible (Figure 7). In order to assess jump height, the SLCMJ test employed an accelerometer (Myotester, Myotest S.A., Sion, Switzerland) which was fixed firmly around the waist using a Velcro strap, immediately superior to the greater trochanter. Finally, the TSHT required the patient to hop throughout a 16-hop agility course (that included forwards, backwards and sideways direction hops) as fast as possible (Figure 8). A stopwatch was used to determine the time taken to cover the course, which was made utilising the Speedy Basic Jump Set (TST Trendsport, Grossholzlein, Austria). A total of three valid hop trials was required for the SHD, MHD, LHD, THD, TCHD and SLCMJ, while two valid hop trials were required for the 6MTH and TSHT. Furthermore, free use of the arms was permitted during all hop tests for consistency.

**DATA AND STATISTICAL ANALYSIS**

Initially, the best score (distance, height or time) for each hop test, on each limb, was employed in the final analysis. Using this best score, LSIs were obtained for each of the eight hop tests, calculated by dividing the peak values on the operated limb by that recorded on the non-operated
limb for all distance/height measures (and by dividing the scores on the non-operated limb by that recorded on the operated limb for the timed measures). For the entire cohort (n=50) as well as specifically for males (n=34) and females (n=16), the LSI means (SD) and ranges were reported, together with the number (and percentage) of patients demonstrating LSIs ≥90% for each hop measure. Analysis of Variance (ANOVA) was employed to evaluate differences in LSIs across all of the functional hop measures, and post-hoc t-tests were employed to investigate where differences existed. Independent t-tests were employed to evaluate any LSI differences in hop measures between males and females. Pearson’s correlations were undertaken to investigate the significance (at the p<0.01 and p<0.05 level) and strength of the association between LSIs for each of the eight varied hop tests. Statistical analyses were undertaken using SPSS version 23.0 (SPSS Inc, Chicago, Illinois, USA). Statistical significance was determined at p<0.05, while the size of the Pearson’s correlations were reported according to Mukaka (0.0-0.3 negligible, 0.3-0.5 low, 0.5-0.7 moderate, 0.7-0.9 high, 0.9-1.0 very high).

An a priori sample size power calculation based on detecting statistically significant differences across the eight hop measures was determined using G-Power (Dusseldorf, Germany). Based on preliminary pilot data undertaken in 20 patients comparing LSIs across the eight functional hop tests assessed as part of the current study, a moderate effect size (d=0.56) was estimated. Therefore, in order to detect significant differences in mean LSIs across the eight hop tests, a minimum sample of n=8 was estimated to reveal differences at alpha 0.05 with 80% power. Ethics was attained from the Hollywood Private Hospital Human Research Ethics Committee (HPH382) prior to patient recruitment and evaluation. Informed consent was received and the rights of the subjects were protected.

RESULTS

The mean age of the recruited cohort was 28.3 (SD 9.1, range 16-47) years with a mean body mass index of 24.6 (SD 2.8, range 18.8-31.4). At the time of review, patients were on average 10.2 (SD 1.4, range 9-12) months post-surgery, and the mean time from injury to their primary ACLR was 10.4 (SD 11.9, range 2-54) weeks.

Table 1 shows the mean (SD) LSI and range for each of the eight hop tests undertaken, for the entire cohort as well as specifically for males and females. For the entire cohort, ANOVA demonstrated significant differences across the eight hop tests (p<0.0001). The mean LSIs for the SHD (95.0%), 6MTH (95.0%), THD (96.1%) and TCHD (95.3%) were all ≥90%, and not significantly different (p>0.05) from each other. These were all significantly greater (p<0.05) than the mean LSIs observed for the MHD (87.3%), LHD (87.5), SLCMJ (83.4%) and TSHT (86.5%), which were all <90% (Table 1). While the LSIs for the MHD, LHD and TSHT were not significantly different from each other (p>0.05), the mean LSI for the SLCMJ was significantly lower (p<0.05) than every other hop test. There were no significant differences (>0.05) for any of the hop LSIs between males and females.

While the majority of patients demonstrated an LSI ≥90% for the SHD (88%), 6MTH (80%), THD (88%) and TCHD (84%), the majority were <90% for the MHD (46%), LHD (50%), SLCMJ (18%) and TSHT (32%) (Table 1). Overall, 36 patients (72%) demonstrated an LSI ≥90% for the combined hop battery of the SHD, 6MTH, THD and TCHD. Only five patients demonstrated an LSI ≥90% for every one of the eight hop tests.
<table>
<thead>
<tr>
<th>Test</th>
<th>Entire Cohort (n=50)</th>
<th>Males (n=34)</th>
<th>Females (n=16)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Range</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥90% LSI, n (%)</td>
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<tr>
<td>SHD</td>
<td>95.0 (5.0)</td>
<td>81.9-105.2</td>
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<td>6MTH</td>
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<td>75.4-116.2</td>
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<td>THD</td>
<td>96.1 (6.3)</td>
<td>77.1-106.5</td>
<td>96.2 (6.2)</td>
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<tr>
<td>TCHD</td>
<td>95.3 (6.6)</td>
<td>79.4-104.9</td>
<td>94.7 (6.5)</td>
</tr>
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<td>64.0-97.7</td>
<td>87.7 (6.7)</td>
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<td>MHD</td>
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<td>62.9-100.0</td>
<td>87.3 (7.6)</td>
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<tr>
<td>SLCMJ</td>
<td>83.4 (9.5)</td>
<td>62.2-104.2</td>
<td>83.8 (8.8)</td>
</tr>
<tr>
<td>TSHT</td>
<td>86.5 (8.9)</td>
<td>64.0-101.3</td>
<td>87.6 (7.8)</td>
</tr>
</tbody>
</table>

SHD = Single Hop for Distance; 6MTH = 6m Timed Hop; THD = Triple Hop for Distance; TCHD = Triple Crossover Hop for Distance; LHD = Lateral Hop for Distance; MHD = Medial Hop for Distance; SLCMJ = Single Leg Countermovement Jump for Height; TSHT = Timed Speedy Hop Test.
Statistically significant (p<0.05) and positive correlations existed across the majority of hop tests (Table 2). High positive correlations (r=0.70-0.80) existed between the SHD, THD and TCHD. Low and moderate positive correlations were observed between the TSHT (r=0.26-0.49), SLCMJ (r=0.20-0.55), MHD (r=0.38-0.63) and LHD (r=0.39-0.63), with each of the other hop tests (Table 2).

DISCUSSION

The most important finding of the current study was that some hop measures (LHD, MHD, SLCMJ and TSHT) demonstrated significantly lower mean LSIs than others (SHD, 6MTH, TCD and TCHD). The majority of patients achieved >90% LSI scores on the four more commonly reported hop tests (SHD, 6MTH, THD, TCHD). In contrast, the majority of patients demonstrated LSIs <90% on the four lesser reported hops (LHD, MHD, SLCMJ, TSHT).

Recent studies have demonstrated an increased re-injury risk if patients RTS without meeting >90% LSI cut-offs, in a range of hop and strength parameters undertaken as part of a test battery.9,10 A four times greater re-injury risk in those who RTS after ACLR was reported by Kyritsis et al. if not meeting the RTS discharge criteria that included an LSI >90% in the SHD, THD and TCHD.10 Grindem et al. also reported a greater re-injury rate if LSIs >90% for quadriceps strength and functional hop symmetry were not met, which included the aforementioned three hop measures, as well as the 6MTH.9 These four hop measures have been reported previously in the form of a hop test battery,11 and the SHD has been reported as one of the most common functional hop measures reported for use in patients after ACLR.22 A systematic review undertaken by Hegedus et al. reported that despite numerous published studies employing hop tests such as the SHD, 6MTH, THD and TCHD, there remains limited and conflicting evidence regarding the reliability, agreement, construct validity, criterion validity and responsiveness of these functional measures.23

Furthermore, it should be acknowledged that despite their widespread use, many of these single limb hop tests are straight line movements (apart from the TCHD which incorporates some multi-directional, albeit not hard cutting hops) and have been criticized for not sufficiently evaluating functional performance in patients following ACLR.17 A recent study by Ebert et al. reported that the TSHT and SLCMJ demonstrated significantly lower mean LSIs in patients after ACLR than the more commonly employed and reported SHD, 6MTH, THD and TCHD, suggesting some hop tests may be more sensitive in detecting side-to-side differences in functional symmetry.18 The TSHT requires multiple forwards, sideways and backwards hops combined as a timed test, which may prove more challenging for patients (hence the lower mean LSIs observed). Admittedly, the ear-
lier Ebert et al.\textsuperscript{18} study did not permit free use of the arms for the SLCMJ as was the case in the current study, though having to propel the body upward against gravity, as opposed to the forwards direction, may still require more demand (strength and power) from the quadriceps muscles to generate height. Finally, the reasons for the significantly lower LSIs on the MHD and LHD can only be speculated. While both require a controlled land and move in side directions which is different to the more traditionally employed hop tests,\textsuperscript{11} anecdotally, it appears harder to generate the power required during the LHD to transition laterally (i.e. factors such as arm swing are better controlled for, unlike the forwards hop measures). The MHD may require a more challenging landing position, whereby the momentum moving medially almost forces the lower limb into a more dynamic valgus position, which may then be harder to land in patients lacking adequate lower limb muscular control. Finally, it should be acknowledged that both of these side hop measures may simply present relatively naïve tasks for the patient. This may create a higher degree of difficulty, thereby presenting greater asymmetry and highlighting potential benefit in their utility. The first hypothesis was that significant variation in lower limb symmetry measures would exist across the eight functional hop tests employed, and those incorporating multi-directional movement would demonstrate greater asymmetry. Overall, the first hypothesis was largely supported.

The current study also investigated the correlation between LSIs across each of the functional hop tests. While statistically significant and positive correlations existed across the majority of hop tests, the strength of these associations varied. The strongest correlations existed between the SHD, THD and TCHD, all distance-based measures incorporating forwards and straight-line movements. The second hypothesis was that the strongest correlations between hop tests would exist for forwards distance-based hop measures, with the weakest correlations observed in those incorporating multi-directional movement. Therefore, this partially supported the second hypothesis and, combined with the similar mean LSIs observed for each of these hop tests, would suggest that the use of any of these three hop tests would provide similar information to the clinician if the presence of functional limb asymmetry was the primary concern. The TSHT, SLCMJ, MHD and LHD demonstrated the weakest correlations with the other hop tests. As outlined above, the TSHT is a timed measure incorporating multi-directional movements which would also support the second hypothesis. While the MHD and LHD are not multi-directional measures, they are also not hop measures in a forwards direction, and it unknown whether this provides rationale for the weaker correlation with the forwards distance tests given they are directions less encountered during activities of daily living.

It is important to note that the current study employed a range of hop measures commonly reported in the literature and/or used routinely through our clinical institution. However, a range of other hop tests have been reported in addition to those employed in the current study including, though not limited to, the triple medial hop for distance,\textsuperscript{24} the 90° medial rotation hop for distance,\textsuperscript{24} the single timed lateral hop\textsuperscript{25} and 30s side hop test,\textsuperscript{15} the timed square hop,\textsuperscript{15} the figure-of-eight timed hop test,\textsuperscript{26} and a drop jump followed by a double hop for distance.\textsuperscript{15} While we sought to manage the role of fatigue via hop test randomisation and providing patients the rest time they felt they required, incorporating more hop tests may have jeop-
ardized this. These other reported hop tests warrant further investigation, given the results of the current study.

Furthermore, it should also be acknowledged that >90% LSI cut-offs are often employed in patients following ACLR\(^3,10\) for more traditional hop tests (including the SHD, 6MTH, THD and TCHD), largely when considering that normative data in healthy subjects (comparing the dominant and non-dominant limb) demonstrates mean LSIs in these hop tests ranging from 98–102%.\(^27\) However, while this study again sought to compare LSIs across the varied hop tests, we are yet to appreciate what LSI may be considered ‘normal’ or ‘abnormal’ for all of these hop measures that lack normative data in a healthy population. While healthy normative mean LSIs of 101–104% (dependent on gender and age) have been reported for the TSHT\(^3\), mean LSIs for the SLCMJ have been reported to range from 102–124% in favour of the dominant limb (albeit this was undertaken with fixed arms, rather than free use of arms as permitted in the current study).\(^3\) To the best of the author’s knowledge, normative LSIs in a healthy population having been presented for the MHD or LHD. Developing a normative dataset for all hop measures remains an area for future research, in order to better appreciate the LSIs observed in these other hop tests in the post-operative ACLR cohort.

The current study acknowledges a number of further limitations. Firstly, the lack of study generalizability should be acknowledged given the pre-defined cohort that was employed, including those undergoing ACLR via a hamstring autograft, those within 16–50 years of age and those specifically 9–12 months post-surgery. The surgical graft method and age range was set to accommodate the majority of patients seen in clinical practice locally, as well as those most likely to be seeking a RTS (which also served as part of the study inclusion criteria). We sought to evaluate patients at 9–12 months given anecdotally this has traditionally been a time that patients transition down a RTS pathway, while existing evidence has reported a reduced re-injury rate in patients returning to pivoting sports after 9 months post-surgery.\(^9\) Secondly, while LSIs are commonly employed to present functional outcomes,\(^13–15\) Wellstandt et al. reported these can overestimate knee function in patients following ACLR.\(^16\) Furthermore, mean LSIs can be misleading given the potential for high LSIs to balance out poor LSIs, hence the current study also presented the amount of patients above and below the reported 90% LSI cut-off for each test. Nonetheless, this study sought to compare LSIs across the varied tests. Thirdly, while existing literature has suggested that an LSI >90% is considered to be ‘normal’ when comparing the ACLR limb to the non-operated limb,\(^12,13\) we are yet to ascertain how applicable this reported 90% cut-off is to different hop tests (i.e. single versus multi-hop measures, or straight line versus multi-directional hop tests). This requires further investigation, though the current study also sought to investigate the presence of significant differences between mean LSIs.

Fourthly, it should be acknowledged that the patients recruited for this study received varied rehabilitation guidance and exercise prescription, which could affect each patient’s ability to undertake each of the varied hop measures. Furthermore, for the current study there were no specific objective criteria employed to essentially ‘clear’ the patient for study participation, apart from that already mentioned including time from surgery and the absence of knee and/or musculoskeletal pain in general that may affect performance. Again, the current study sought to investigate differences across functional hop tests (within patients), rather than between patients. Fifthly, while the hop battery was randomized in an attempt to mitigate any fatigue affects, the rest period between the hop trials was not standardized and was dictated by the patient’s perceived readiness to proceed. This may affect the results across patients, albeit it was decided upon to ensure that all fitness levels could be accommodated and each patient was not forced to progress before they felt ready (as would have been the case with a pre-determined rest period). Finally, it should be acknowledged that functional hop symmetry is only one part of the larger and more comprehensive RTS decision making process. Furthermore, these performance-based hop measures seek to evaluate distance or time, and lack an objective assessment of lower limb biomechanics which may be associated with the risk of secondary ipsilateral and contralateral ACL rupture.\(^28\) Welling et al. recently reported clinically relevant altered movement patterns in patients after ACLR in the SHD, despite LSIs >90%,\(^29\) while a recent systematic review and meta-analysis outlined the risk of using distance only during the SHD given the additional presence of several kinetic and kinematic deficits commonly observed in patients following ACLR.\(^30\)

**CONCLUSION**

In the current study, more commonly reported and em-
ployed functional hop measures (SHD, 6MTH, THD and TCHD) demonstrated mean LSIs >90%, with the majority of patients (80-88%) demonstrating an LSI >90% for each hop test as assessed at 9-12 months following ACLR undertaken via a hamstring tendon autograft. However, significantly lower mean LSIs (<90%) were observed in lesser reported functional hop measures (MHD, LHD, SLCMJ and TSHT), with the majority of patients (54-78%) demonstrating an LSI <90% for each hop test. The current results would suggest that the latter four hop tests are better at identifying side-to-side functional asymmetry in patients following ACLR. These functional hop measures should be considered in both future research settings and the clinical environment. While a battery of hop measures (rather than a single hop test) is recommended in the evaluation of patients after ACLR, the therapist must be confident that the hop tests they include are indeed able to assess higher level functional capacity if purpose is to detect the presence of lingering functional deficits in these patients prior to RTS.

CONFLICT OF INTEREST STATEMENT
No benefits in any form have been received or will be received from a commercial party related to the subject of this article.

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ETHICS
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Background
Professional ballet dancers suffer high injury rates and are less likely than other athletes to specifically train to improve muscular strength, coordination, agility, speed and motor control because of heavy training demands, aesthetic appearances and financial barriers.

Hypothesis/Purpose
The purpose of this study was to examine the effects of a supplemental conditioning program on professional and pre-professional contemporary ballet dancers. The authors hypothesized that those participating in a training program would reduce injury rate by improving their motor control, stability, balance and physical function. The authors aimed to observe the feasibility and qualitative phenomena related to a conditioning program from the dancer's perspective.

Study Design
A mixed-methods study; within subject quasi-experimental design and qualitative interviews.

Methods
Six professional classical and contemporary ballet dancers completed the five-week conditioning and injury prevention training program. Non-parametric analysis of baseline, posttest and four-month follow-up physical performance measures, subjective outcomes, and qualitative follow-up interviews, were reported.

Results
Significant post-test improvements included: The Dance Functional Outcome Survey ($Z = -2.2, p = 0.04$), composite Modified Star Excursion Balance Test ($Z = -2.2, p = 0.03$ bilaterally), Single Leg Hop for Distance ($Z = -2.02, p = 0.04$), and Upper Extremity Closed Kinetic Chain Test ($Z = -2.03, p = 0.04$). Significant changes from baseline to the four-month follow up remained for: (1) Dance Functional Outcome Survey ($Z = -2.2, p = 0.05$), (2) Single Leg Hop for Distance ($Z = -2.2, p = 0.03$), and (3) Modified Star Excursion Balance Test composite maximum reach for the left lower extremity ($Z = -2.2, p = 0.03$).

Conclusion
Completing a conditioning and prevention program for professional ballet dancers was related to improved function, balance, hop distance/stability and upper extremity stability. Dancers found the program beneficial, identified barriers to participation, and

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elucidated factors making the program feasible and successful. More research is necessary to determine the effect of such programs on injury incidence.

Level of evidence

3b

INTRODUCTION

Ballet dancers are at high risk of sustaining musculoskeletal injuries, especially due to the multitude of technical movements they perform repetitively at extreme ranges of joint motion. Combining both the professional and pre-professional levels, overuse accounts for 65.9% of dance injuries. Smith et al. indicated that amateur and professional dancers have a combined incidence of 1.09 injuries per 1000 dance hours. While several authors have indicated that dance injuries most commonly affect the foot and ankle, the next most commonly injured regions were the lumbar spine, knee, and hip. These injuries create a substantial burden for dancers and companies alike; the costs of time-loss due to injury, medical expenses, risk of premature retirement, and increased risk for chronic musculoskeletal conditions impact all constituents of the dance community.

Despite the traditional reputation of ballet as an "art," professional dancers are commonly regarded as athletes based on the physical demands they sustain through long hours of technical training, rehearsals, and performances. Dancers must possess a high level of fitness, strength, coordination, agility, speed, and motor control to perform at the elite level with minimal injury risk. However, professional ballet dancers are less likely than other athletes to specifically train these areas of fitness. Dancers commonly teach and work outside of their company dancer positions in order to supplement their limited income from dancing alone. The additional time, financial and physical constraints associated with their supplemental work limit the feasibility of adding further training to their schedules. Many dancers may avoid strength and agility training due to the belief that these fitness activities may cause hypertrophy of muscle, negatively impacting their aesthetic appearance. Subsequently, dancers have been deemed "not as well-conditioned" as other athletes. Similar to other sports, the high prevalence for overuse injuries in dance has been linked to strength, aerobic fitness, and motor control deficits. Training programs have been shown to improve such impairments in this population.

Although injury prevention and screening programs for lower extremity injuries have been commonly utilized in sports such as soccer, similar programs have only recently been proposed for professional dancers. Though initially recommended three decades ago, the literature regarding the effects of ballet injury prevention programs remains limited, and no studies have sought to standardize the elements of such programs. Initial investigations regarding the benefits of supplemental fitness training showed positive results for decreasing pain, mixed results for improving aerobic capacity, and no significant strength improvements. Mistiaen et al. reported positive effects on fitness without affecting aesthetic appearance. Although dysfunctional movement patterns have been associated with injury, the effects of motor control training in the professional dance population have not been thoroughly studied.

The purpose of this study was to examine the effects of a supplemental conditioning program on professional and pre-professional contemporary ballet dancers. The authors hypothesized that those participating in a training program would reduce injury rate by improving their motor control, stability, balance and physical function. The secondary purposes were to: (1) determine whether professional ballet dancers' motor control, stability, balance, and physical function improved by participating in a conditioning and injury prevention program, (2) determine if motor control, balance and stability were related to injury incidence, (3) determine if subjective dance-specific function, as measured with the Dance Functional Outcome Survey (DFOS), correlated with injury in professional and pre-professional contemporary ballet dancers, and (4) observe the feasibility and qualitative phenomena related to a conditioning program from the dancer's perspective.

METHODS

PARTICIPANTS

This sample of convenience included uninjured adult dancers from a small professional contemporary ballet company who were recruited through word of mouth and a brochure that was shared with the company. The initial sample consisted of 11 dancers: eight professionals, one apprentice and two trainees. Participation was voluntary. All subjects who elected to participate granted informed consent. Anonymity and confidentiality were maintained throughout the study. Two dancers from the initial sample were excluded due to sustaining dance-related injuries prior to the start of the training program.

STUDY DESIGN

The study was a mixed methods quasi-experimental design with a volunteer sample of professional dancers from one company. The project was approved by the Cleveland State University Institutional Review Board. The final sample consisted of six dancers who were informed that data would be submitted for publication. Subject confidentiality was protected. A power analysis to determine sample size was not possible in this study. Dancers are a unique athletic population. Previous data with estimates of difference or variance for dancers and these outcome measures were not available to perform a power analysis prior to this feasibility study.

DEMOGRAPHICS AND DANCE EXPERIENCE

Characteristics of the sample were collected via survey on the day of baseline testing. Dancers were asked for their
age, gender, highest level of education, and years of dance experience.

DANCE FUNCTIONAL OUTCOME SURVEY

All dancers completed the DFOS at baseline, immediately post-conditioning class, and at the four-month follow-up. The DFOS is currently the only dance-specific subjective functional outcome measure and focuses on general activities of daily living and dance-specific technique. Very recent investigations regarding the psychometric properties of this tool revealed high test-retest reliability, internal responsiveness over time, sensitivity and internal consistency. The DFOS demonstrated strong construct validity (vs. SF-36 PCS), scale uni-dimensionality, and the absence of both floor and ceiling effects.

PHYSICAL PERFORMANCE TESTS

A battery of physical performance tests (PPTs) was performed at baseline prior to beginning the conditioning class, within the week following completion of the last class, and at a four-month follow-up. The PPTs selected were previously validated as effective measures of balance, stability, and motor control. They were performed as described by the authors listed in Table 1, with testing completed by the same raters at baseline and each subsequent testing period.

NEUROMUSCULAR CONDITIONING AND INJURY PREVENTION CLASS

The conditioning and injury prevention class was performed in the studio twice a week for 30 minutes over the course of five weeks, with the first session each week taught by a licensed physical therapist who was board certified in orthopedics. The second supplemental session each week was led by one dancer liaison who attended the class earlier in the week. The selected dancer had experience teaching group exercise classes. She reviewed the exercises with the dancers with the guidance of a handout outlining the program.

The neuromuscular conditioning and injury prevention class was developed together by the board certified orthopedic physical therapy specialist who taught the class, and the physical therapist specialty-trained in strength and conditioning. Similar to previous programs, this course began with basic movement pattern injury prevention exercises known to be effective in other sport populations. It initially emphasized mechanics and correction of movement faults with basic exercises such as bridges, planks, single leg deadlifts, lunges, squats, step ups, and jumping. The program then progressed to more dance-specific movement system patterns as the course advanced (Appendix 1). The full program consisted of a dynamic warm-up, agility training, plyometrics and strength training (Table 2). Previous authors have recommended that injury prevention programs include these components. As suggested previously, verbal and tactile feedback to correct faulty movement patterns were given concurrently while performing each exercise. Dancers were educated regarding the targeted anatomical regions, desired movement patterns, typical compensations, likely mechanisms for injury, intervention rationale, and how the techniques might both reduce injury and enhance performance. Dancers were taught how basic component training was relevant to and translated to improving their traditional ballet combinations.

STATISTICAL ANALYSIS

Inferential statistics. Changes between baseline and post-conditioning PPTs were assessed using the Wilcoxon signed-rank test, which is a paired difference test of mean rank used for single sample, repeated measurements. Statistical significance was set at $p<0.05$. This non-parametric test is inherently conservative and is used with small sample sizes to reduce assumptions about data distribution normality.

QUALITATIVE ANALYSIS

Phenomenological interview. The purpose of this mixed methods phenomenological analysis was to understand the experience or phenomenon from the dancers’ point of view. The researchers were interested in learning if dancers felt a cross training program had benefits and value. If conditioning was beneficial, what recommendations were there for other dancers? This information was obtained through structured interviews by one researcher four months after the conditioning class. The 30-minute interview consisted of eight open-ended qualitative questions. All interviews were audio recorded and transcribed by a member of the research team who did not teach the program, interview dancers, or develop the study design.

Phenomenological analysis. To maximize credibility of the study, several methods were used: triangulation of researchers’ interpretations, sampling for diverse perspectives, and rich descriptions to support thematic categories. First, each transcript was reviewed by the authors individually to look for key phrases in each interview question. Next,

Table 1: Physical Performance Tests

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor control</td>
<td>2 Motor control tests:</td>
</tr>
<tr>
<td></td>
<td>† Knee Lift Abdominal Test</td>
</tr>
<tr>
<td></td>
<td>‡ Standing Bow</td>
</tr>
<tr>
<td>Balance</td>
<td>Modified Star Excursion Balance Test†</td>
</tr>
<tr>
<td>Ankle and Knee Stability</td>
<td>One Leg Hop for Distance‡</td>
</tr>
<tr>
<td>Hip Stability</td>
<td>Medial Triple Hop Test†</td>
</tr>
<tr>
<td>Upper Extremity Stability</td>
<td>Closed Kinetic Chain Upper Extremity Stability Test§</td>
</tr>
</tbody>
</table>

* Roussel, Njis, Mottram et al.† Hegedus, McDonough, Bleakley et al.‡ Kivlan, Garcia, Clemente et al.§ Goldbeck and Davies.
Table 2: Complete 5-week Conditioning Program

<table>
<thead>
<tr>
<th>Week</th>
<th>Exercises</th>
<th>Plyometrics</th>
<th>Agility</th>
<th>Strength</th>
</tr>
</thead>
</table>
| 1    | • Forward jogging  
• High knees  
• Butt kicks  
• Alternating front kick with toe touch  
• Alternating heel walk dynamic hamstring stretch with toe reach | • Jumps scissor jump  
• Wall Taps  
• DL hop forward, backward and over lateral line  
• Controlled step down from stage  
• Step up onto 2 feet stage | • Forward SL hops  
• Lateral SL hops  
• Medial SL hops two feet left, 1 foot in, 2 feet right | • High plank  
• Side plank each side  
• Prone gluteal set with bilateral UE shoulder flexion holds  
• Straight leg raises  
• Bridges  
• Squat with TheraBand biceps curl  
• Pistol squats  
• Lunge with overhead shoulder press  
• SL Romanian deadlift  
• Push ups  
• Bench dips  
• Inverted rows at bar |
| 2    | • Alternating front kick with toe touch  
• Alternating heel walk dynamic hamstring stretch with toe reach  
• Carioca  
• High Knee Skip | • Scissor jumps  
• Wall taps with side facing wall  
• DL zip zag hops forward and retro  
• Controlled step off stage landing in to deep squat  
• Stage step ups with high knee | • Forward SL hops  
• Lateral SL hops  
• Medial SL hops two feet left, 1 foot in, 2 feet right | • High to low plank  
• Side-plank with hip dip/raise  
• Prone gluteal set with bilateral UE shoulder flexion/bilateral LE extension holds  
• Bridges with marching  
• Backwards lunge  
• SL Romanian deadlift with arms forward  
• Push up (isometric hold) with opposite shoulder tap  
• Bench dips (isometric hold with tip toes)  
• TheraBand rows  
• Overhead squats with TheraBand |
| 3    | • Jogging  
• Marching  
• Lateral shuffle (face same direction)  
• Lunge walk (1x down & back)  
• "Inchworm" forward fold to high plank walkout (1x down & back) | • Grand plie squat jump  
• Split squat jump  
• Alternate leg push off  
• Drop freeze | • Hopscootch  
• Lateral SL hops (skip a box)  
• Medial SL hops (skip a box)  
• start both feet in: right lateral out, left forward, right forward in, left lateral out, right forward, left forward in (repeat) | • SL squat reaching in anterior, medial, lateral, and posterior directions with non-stance leg  
• Pilates roll out (eccentric abdominals)  
• SL stiff leg deadlift with arms overhead  
• High plank opposite knee to opposite elbow  
• Rellevé lunge-hold into forward lunge, right lunge, back wards lunge, left lunge  
• Reverse crunches |
| 4    | • Alternating front kick with toe touch  
• Carioca  
• High knee skip  
• Lunge with overhead side reach  
• "Inchworm" forward fold to high plank walkout | • Single-arm alternate leg bound  
• DL box jumps  
• Drop Freeze  
• Depth jumps with lateral movement  
• SL forward hops for distance  
• SL medial hop for distance | • Forward SL hops with arms behind back  
• Lateral SL hops (skip a box)  
• Medial SL hops (skip a box) | • Y Balance SL Squat: -anterior, posterior-medial, & posterior-lateral directions  
• SL stiff leg deadlift with arms overhead and calf raise  
• Rellevé lunge -hold into forward, right, retro, & left lunge  
• Bridges-hips abducted vs TheraBand & alternating hip flexion  
• Plank bird dog  
• Push up with contralateral hand taps  
• TheraBand rows  
• TheraBand horizontal abduction |
the authors met as a group to confirm the key phrases found in each interview question and compile the results. Then, the authors reviewed the key phrases individually to look for main themes in each question across all subjects. The main themes that each individual determined for each interview question were placed in a table organized by the eight guiding questions. The group agreed upon the main themes.

**Injury tracking.** Injury tracking within the study period was conducted via survey at the four-month follow-up interview. Dancers indicated any time lost from dance or time requiring modified activity during the course and four-month follow-up period.

**RESULTS**

**SUBJECTS**

Of the 11 dancers initially tested, five dancers did not complete the program. Two were excluded prior to the start of the study. Three additional dancers dropped out for the following reasons: (1) concern regarding previous surgeries, (2) a leave of absence from the company, and (3) schedule constraints. Thus, the final sample consisted of six dancers. Descriptive statistics for participating subjects were calculated (Table 3).

**INFERENTIAL FINDINGS**

**Post-conditioning.** Results from the Wilcoxon signed-rank tests for baseline to post-conditioning change in the DFOS and PPTs are included in Table 4. Statistically significant changes for the DFOS and three of the six PPTs were found. Immediately following the conditioning program, the DFOS was significantly improved ($p = 0.04$). Dancers also showed improved balance on the composite Modified Star Excursion Balance Test (mSEBT) bilaterally ($p = 0.05$ for both the right and left lower extremity), improved Single Leg Hop for Distance ($p = 0.04$), and improved performance on the Upper Extremity Closed Kinetic Chain test ($p = 0.04$). No statistically significant changes were noted with the KLAT, Standing Bow Test, or the Medial Triple Hop Test.

**Four-month follow-up.** Statistically significant changes from initial testing to the four-month follow-up remained for the following tests: (1) DFOS ($p = 0.03$), (2) Single leg hop for distance ($p = 0.05$), and (3) mSEBT composite maximum reach for the left lower extremity ($p = 0.03$). The Upper Extremity Closed Kinetic Chain test ($p = 0.08$) and the mSEBT composite reach right ($p = 0.08$), anterior reach right ($p = 0.12$) and left ($p = 0.23$) were not statistically significantly different from baseline (Table 4). Furthermore, none of the tests found non-significant at the initial follow-up became statistically significant at the four-month follow-up.

**QUALITATIVE FINDINGS**

Findings from the phenomenological analysis of the follow-up interview were categorized into common themes across the questions (Table 5). Half of the participants reported they were motivated to participate in the conditioning course to improve their performance. With respect to strengths and limitations, 83.3% of dancers believed their leg strength and endurance were their strongest attributes, and 66.7% reported their stability, balance and landing technique with jumping were their greatest limitations. The dancers found exercises targeting core stability (66.7%), upper body strength (50%) and leg strength (50%) to be the most beneficial exercises, while 66.7% of those same participants reported they no longer continued doing core exercises, specifically bridges and planks, after the course.

### Table 3: Descriptive Statistics

<table>
<thead>
<tr>
<th>Education</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>College</td>
<td>50%</td>
</tr>
<tr>
<td>Some College</td>
<td>33%</td>
</tr>
<tr>
<td>High School</td>
<td>16%</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>33.30%</td>
</tr>
<tr>
<td>Female</td>
<td>66.70%</td>
</tr>
<tr>
<td><strong>Dance Training</strong></td>
<td></td>
</tr>
<tr>
<td>10-12 years</td>
<td>50%</td>
</tr>
<tr>
<td>17-20 years</td>
<td>50%</td>
</tr>
<tr>
<td>Professional Dancer</td>
<td>66.70%</td>
</tr>
<tr>
<td>Apprentice/Trainee</td>
<td>33.30%</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>22.8 (SD 1.47)</td>
</tr>
</tbody>
</table>

| DL = double leg, UE= upper extremity, SL= single leg, LE = lower extremity |

<table>
<thead>
<tr>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Alternating front kick with toe touch</td>
</tr>
<tr>
<td>• Butt Kickers</td>
</tr>
<tr>
<td>• High knee skip</td>
</tr>
<tr>
<td>• Lunge with twist</td>
</tr>
<tr>
<td>• ‘Inchworm’ forward fold to high plank walkout</td>
</tr>
<tr>
<td>• Foot touches</td>
</tr>
<tr>
<td>• SL box jumps</td>
</tr>
<tr>
<td>• SL Depth jump</td>
</tr>
<tr>
<td>• forward SL hop for distance</td>
</tr>
<tr>
<td>• Medial SL hop for distance</td>
</tr>
<tr>
<td>2 ladder lengths each:</td>
</tr>
<tr>
<td>• Forward SL hops</td>
</tr>
<tr>
<td>• Lateral SL hops</td>
</tr>
<tr>
<td>• Medial SL hops</td>
</tr>
<tr>
<td>• Y Balance SL Squat: -anterior, posterior-medial, &amp; posterior-lateral directions</td>
</tr>
<tr>
<td>• Reaching Rond de Jambe</td>
</tr>
<tr>
<td>• Relevé lunge - hold into forward, right, retro, &amp; left lunge</td>
</tr>
<tr>
<td>• Relevé Plié</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5: Descriptive Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descriptive Statistics</td>
</tr>
<tr>
<td><strong>Education</strong></td>
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<tr>
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</tr>
<tr>
<td>Some College</td>
</tr>
<tr>
<td>High School</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
</tr>
<tr>
<td>Male</td>
</tr>
<tr>
<td>Female</td>
</tr>
<tr>
<td><strong>Dance Training</strong></td>
</tr>
<tr>
<td>10-12 years</td>
</tr>
<tr>
<td>17-20 years</td>
</tr>
<tr>
<td>Professional Dancer</td>
</tr>
<tr>
<td>Apprentice/Trainee</td>
</tr>
<tr>
<td><strong>Age</strong></td>
</tr>
<tr>
<td>Mean</td>
</tr>
</tbody>
</table>
The Impact of Dance-Specific Neuromuscular Conditioning and Injury Prevention Training on Motor Control, Stability,...

Table 4: Means and Pre-test to Post-test Wilcoxon Signed-Rank Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Pre-Test</th>
<th>5 Week Follow-Up</th>
<th>4 Month Follow-Up</th>
<th>Pre-Test to 5 Week Follow-Up</th>
<th>Pre-Test to 4 Month Follow-Up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Z</td>
<td>p-value</td>
</tr>
<tr>
<td>mSEBT Composite Right (cm)</td>
<td>260.08 (18.0)</td>
<td>291.58 (30.50)</td>
<td>273.33 (28.86)</td>
<td>-2.2</td>
<td>0.028*</td>
</tr>
<tr>
<td>mSEBT Composite Left (cm)</td>
<td>260.96 (17.6)</td>
<td>296.58 (34.25)</td>
<td>276.41 (27.28)</td>
<td>-2.2</td>
<td>0.028*</td>
</tr>
<tr>
<td>mSEBT Maximum Anterior Reach Right (cm)</td>
<td>64.33 (1.94)</td>
<td>76.91 (12.65)</td>
<td>71.5 (10.94)</td>
<td>-1.99</td>
<td>0.046*</td>
</tr>
<tr>
<td>mSEBT Maximum Anterior Reach Left (cm)</td>
<td>66.42 (3.29)</td>
<td>79.75 (15.09)</td>
<td>71.1 (10.87)</td>
<td>-2.21</td>
<td>0.027*</td>
</tr>
<tr>
<td>Single Leg Hop for Distance (cm)</td>
<td>119.59 (12.32)</td>
<td>147.63 (25.02)</td>
<td>145.70 (17.23)</td>
<td>-2.02</td>
<td>0.043*</td>
</tr>
<tr>
<td>Closed Kinetic Chain Upper Extremity Stability Test (taps/15 sec)</td>
<td>25.44 (3.18)</td>
<td>31.27 (4.28)</td>
<td>27.5 (2.69)</td>
<td>-2.03</td>
<td>0.042*</td>
</tr>
<tr>
<td>Medial triple hop Right (cm)</td>
<td>407.81 (41.13)</td>
<td>402.44 (65.75)</td>
<td>394.08 (70.22)</td>
<td>-0.14</td>
<td>0.893</td>
</tr>
<tr>
<td>Medial Triple Hop Left (cm)</td>
<td>417.55 (50.52)</td>
<td>408.58 (79.9)</td>
<td>398.16 (88.25)</td>
<td>-0.37</td>
<td>0.715</td>
</tr>
<tr>
<td>Dance Functional Outcome Scale</td>
<td>80.17 (5.26)</td>
<td>83.16 (3.92)</td>
<td>85.5 (4.08)</td>
<td>-2.2</td>
<td>0.042*</td>
</tr>
<tr>
<td>Standing Forward Bow</td>
<td>All full &amp; painless</td>
<td>All full &amp; painless</td>
<td>All full &amp; painless</td>
<td>No significant change</td>
<td>No significant change</td>
</tr>
<tr>
<td>Abdominal Knee Lift Test Right (mmHg)</td>
<td>9.00 (4.8)</td>
<td>12.00 (3.57)</td>
<td>13.33 (7.0)</td>
<td>-1.38</td>
<td>0.17</td>
</tr>
<tr>
<td>Abdominal Knee Lift Test Left (mmHg)</td>
<td>11.0 (7.1)</td>
<td>16.83 (10.04)</td>
<td>8.0 (2.82)</td>
<td>-1.21</td>
<td>0.23</td>
</tr>
</tbody>
</table>

ended.

The dancers did express concern regarding several barriers which may preclude their participation in similar conditioning classes. Most notably, 83.3% of those interviewed reported that time was their greatest barrier. The convenience of this course being brought to them made it more feasible to fit into their schedules. Money and scheduling were also major concerns, with 66.7% of dancers reporting these obstacles to participating. Even with these barriers considered, the participants unanimously agreed that the course was beneficial for both professional and pre-professional dancers. This group was evenly split, with 50% reporting it would be most beneficial for dancers before 8th grade, while the other 50% noted it would be best suited to target older dancers in 8th grade or above. All 6 dancers reported no time loss due to injury. None of the participants reported a need to modify their dance activity secondary to injury.

DISCUSSION

Many authors have proposed the need for supplemental conditioning programs to improve dancers’ fitness and decrease injury risk factors. However, minimal research exists outlining conditioning program design, or the effects of such programs on injury risk factors. It was hypothesized that using a conditioning program similar to other injury prevention programs for mainstream athletics, with some dance-specific components, would improve physical function in areas previously identified as predicting injury in other sports, as well as dancers’ perception of their function. Investigating the effects of risk-factor specific conditioning on validated physical performance measures is crucial for determining how such programs may or may not influence injury risk factors. It is a necessary preliminary step to determining the effects of such conditioning programs on injury incidence and attempting to design a program that might be utilized by dance companies to minimize overuse injuries.

This study is the first to investigate the impact of neuromuscular conditioning on dance function, motor control, stability and balance in professional and pre-professional ballet dancers. A mixed-methods model was used to gain a more thorough understanding of the results and how the proposed conditioning program influenced the dancer participants. Following the dance-specific conditioning program, improvements were noted in dance function, knee/ankle stability and balance, but not in lumbo-pelvic motor control or hip stability. The phenomenological analysis provided insight into perceived benefits of the program, mo-
Table 5: Qualitative Themes

<table>
<thead>
<tr>
<th>Questions</th>
<th>(Participants)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>What motivated you to participate in this study?</strong></td>
<td></td>
</tr>
<tr>
<td>Knowing baseline/limitations (16.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “I wanted to as a dancer, see where my baseline level was.”</td>
<td></td>
</tr>
<tr>
<td>Helping limitations become strengths (33.33% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “I think as dancers, we all want to know our bodies really well. We want to know our strengths and our limitations. We want to know how to help the limitations become strengths.”</td>
<td></td>
</tr>
<tr>
<td>Cross training opportunity (33.33% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Well for one I wanted to cross train. That’s always a priority, as dancers, so we can keep our bodies functioning to the highest capacity.”</td>
<td></td>
</tr>
<tr>
<td>Improve performance (50% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Well as a dancer my body is definitely my instrument, so I am always looking for new ways to improve it and make it better and make it function at the highest capacity that it can. So, when I [had] the opportunity to work...in ways I had never worked before it was a no brainer, I had to jump on it.”</td>
<td></td>
</tr>
<tr>
<td><strong>What did you learn about your physical capacity, strengths, and limitations through participation in the class?</strong></td>
<td></td>
</tr>
<tr>
<td>They learned their strengths were leg strength and endurance (83.33% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “My strength. I am stronger than I thought on my legs, jumping and landing on one foot.”</td>
<td></td>
</tr>
<tr>
<td>- “My legs are strong. And I wouldn’t say necessarily strength, but also endurance. I can really exert myself.”</td>
<td></td>
</tr>
<tr>
<td>They learned their limitations were balance/stability and jumping/landing technique (66.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “My limitations were just landing on this left ankle- so some of the jump strength trainings, that we did, which was important, I just couldn’t really get through all that.”</td>
<td></td>
</tr>
<tr>
<td>- “I found that my arms and upper body need to be strengthened.”</td>
<td></td>
</tr>
<tr>
<td>- “I feel that a lot of times with impact I lack control and my flexibility tends to get the best of me and so these exercises were very helpful in realizing where my alignment was off and where I needed to work on strengthening and what exactly my body was doing.”</td>
<td></td>
</tr>
<tr>
<td>- “Balance was another thing that I found that I wasn’t aware that I was weaker in.”</td>
<td></td>
</tr>
<tr>
<td><strong>What exercises, if any, did you find to be most beneficial or meaningful?</strong></td>
<td></td>
</tr>
<tr>
<td>Core stability/abdominals (66.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Definitely the different stability exercises we did such as the one-legged squats, we did a lot of bridges on the floor, things like that. Planking, a lot of that kind of thing was really helpful just because those are exercise that I think as dancers we all know we should do but we don’t devote the time to them.”</td>
<td></td>
</tr>
<tr>
<td>Ankle/Leg focus on stability (33.33% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Definitely all of the single leg jumps, and single leg fall downs, when we would stand up on the stage and come down on one foot and jumps up.”</td>
<td></td>
</tr>
<tr>
<td>Upper body strength (50% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “I loved the work with the bands...upper body training with the Thera Bands...new core activities.”</td>
<td></td>
</tr>
<tr>
<td>Leg/quad strength (50% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “The lateral jumping that we did across the floor helped. I could strengthen my muscles and the outside of my legs; it aided in balance, which was one of my limitations.”</td>
<td></td>
</tr>
<tr>
<td><strong>What exercises from the class, if any, do you still perform and why?</strong></td>
<td></td>
</tr>
<tr>
<td>Core exercises (Bridges/Planks) (66.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Really anything that really isolated one leg as opposed to both...a lot of the other stability stuff like the bridges and planks.”</td>
<td></td>
</tr>
<tr>
<td>Stopped doing most exercises (16.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “I stopped doing most of them.”</td>
<td></td>
</tr>
<tr>
<td>Lunges (33.33% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Again, things that I struggled with like any kind of one-legged squat, for sure, or lunge.”</td>
<td></td>
</tr>
<tr>
<td>- “I do some of the alternating lunges and some of the upper body strength that we did with Thera Bands.”</td>
<td></td>
</tr>
<tr>
<td><strong>What do you see as possible barriers for professional dancers to do a similar conditioning class?</strong></td>
<td></td>
</tr>
<tr>
<td>Time - Fitting in (unless brought to us) (83.33% of participants)</td>
<td></td>
</tr>
<tr>
<td>- Time - working a million jobs and timing of classes</td>
<td></td>
</tr>
<tr>
<td>- Difficult to get to a class unless it is brought to us</td>
<td></td>
</tr>
<tr>
<td>Money - organizational companies don’t provide it, can’t afford teachers, can’t afford classes on own) (66.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- Organizational - “most companies don’t respect it to put it into the schedule or they are maximizing time for dance specific things”</td>
<td></td>
</tr>
<tr>
<td>- Money - “organization funds, company doesn’t have funds to pay a teacher or a fitness facility.”</td>
<td></td>
</tr>
<tr>
<td>- Barriers are money - “free for us, but if we had to pay it would be a deal breaker.”</td>
<td></td>
</tr>
<tr>
<td>Scheduling - time of day (not good before class) (66.67% of participants)</td>
<td></td>
</tr>
<tr>
<td>- Different schedules to coordinate group class.</td>
<td></td>
</tr>
<tr>
<td>- “Before class was a challenge because impact from jumping was a little much with the addition of what dancers were already doing.”</td>
<td></td>
</tr>
<tr>
<td>- “Timing - we would like to do it at the end of the day, so we don’t fatigue before class.”</td>
<td></td>
</tr>
<tr>
<td><strong>Would you recommend similar conditioning classes for dancers at your level and why?</strong></td>
<td></td>
</tr>
<tr>
<td>Unanimous yes- liked doing the class in a group (increased motivation and comradery of organization), shows limitations, helps improve strength, stability and balance. (100% of participants)</td>
<td></td>
</tr>
<tr>
<td>- “Yes, aided in comradery and brought the organization together, increased motivation and energy.”</td>
<td></td>
</tr>
<tr>
<td>- “Yes, definitely, it is a good balance and it keeps you healthy. Prefer to do a group as a lot of the energy and motivation.”</td>
<td></td>
</tr>
<tr>
<td>- “Would recommend conditioning classes for dancers at our level because cross training is important.”</td>
<td></td>
</tr>
</tbody>
</table>
• “Yes - helped find exercises to help with limitations; helped alignment, helped improve balance and strength, knees to toes.”

<table>
<thead>
<tr>
<th>Would you recommend a conditioning class with similar principles for any other level(s) of dance and why?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes - important before professional level (100% of participants)</td>
</tr>
<tr>
<td>Half said as kids to develop good technique young (before 8th grade) (50% of participants)</td>
</tr>
<tr>
<td>• “Recommend for all levels of dance and preventing setting up bad habits.”</td>
</tr>
<tr>
<td>• “Yes, at all levels, especially lower levels and all other forms of dance. Lower levels because if you start right with the basics you can perform easier.”</td>
</tr>
<tr>
<td>• “Absolutely, especially when you are a kid...Building strength from a young age would teach us how and why our bodies work the way that they do.”</td>
</tr>
<tr>
<td>Half said 8th grade and older through trainee, pre-professional levels including high school and college (50% of participants)</td>
</tr>
<tr>
<td>• “With students a conditioning class should be done weekly, definitely for 8th grade and up. Younger levels (elementary) are building coordination and motor skills, while in middle school and 8th grade, they can build their concept of alignment.”</td>
</tr>
<tr>
<td>• “Recommend to kids teaching now, but hard to teach a 12-year-old to get involved with this on their own.”</td>
</tr>
<tr>
<td>• “Recommend for trainee or apprentice like pre-professional students to bridge the gap to a professional dancer. Pre-professional dancers are more likely over exert themselves and get injured. A class like this would open their eyes and make them less inclined to injury as they continue to push.”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Is there anything else you wish the conditioning class would have covered?</th>
</tr>
</thead>
<tbody>
<tr>
<td>More core stabilization and less impact/jump training (33.33% of participants)</td>
</tr>
<tr>
<td>• “Definitely work on upper body strength and core stabilization more than jump training.”</td>
</tr>
<tr>
<td>• “More core stability/more low impact rather than jumps.”</td>
</tr>
<tr>
<td>Could have been more dance specific (33.33% of participants)</td>
</tr>
<tr>
<td>• “The active stretching/Pilates/yoga for warm up could be more dance specific.”</td>
</tr>
<tr>
<td>• “Individualized exercise for dancers. Could be even more ballet specific.”</td>
</tr>
</tbody>
</table>

Table 6: Knee Lift Abdominal Test Pressure Variation Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Left Side</th>
<th></th>
<th>Right Side</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Current Study (mmHg)</td>
<td>11</td>
<td>4-24</td>
<td>9</td>
<td>4-18</td>
</tr>
<tr>
<td>Previous Study (mmHg)</td>
<td>48</td>
<td>44-60</td>
<td>47.2</td>
<td>44-54</td>
</tr>
</tbody>
</table>

tivation for and barriers to participation in similar conditioning programs. For example, dancers reported which conditioning exercises were perceived as most beneficial, and which exercises were continued independently after the program. They were most motivated to learn of their strengths and weaknesses, and methods to improve upon their limitations. The most common barriers to such programs are time and money. All dancers would recommend similar conditioning classes to other dancers.

Previous research investigated the effects of a conditioning program, which included motor control training, endurance, and strength training, on aerobic capacity and strength.12 The chosen interventions did not yield significant improvements with the study’s included objective test measures, but their measures did not examine the effect of the program on motor control. The same lead author25 previously described the KLAT and standing bow test as motor control measures which could predict injury in the lower extremities and lumbar spine. A similar lack of improvement with these same tests was noted here. While the KLAT and Standing Bow Test were validated for predicting injury in the original study,12 baseline measures in the current sample showed much less pressure variation (Table 6) and higher performance, respectively.

These findings indicate that these measures may have an inherent ceiling effect and may not be sensitive-enough for professional dancers. It is possible that, because of their initially superior scores and lack of injury incidence during the study period, the dancers in this study also had a decreased injury risk compared to those studied previously.12 If such is the case, further development of more sensitive dance-specific PPTs for motor control and stability in professional-level dancers may be warranted. Improvements were noted in balance and knee/ankle stability, as evidenced by improvements in the mSEBT and the Single Leg Hop for Distance test, respectively. While the SEBT and Y-balance tests have been widely studied, only four publications prior to 2016 used one of these tools to investigate injury risk in sport.17 These studies demonstrated that a mSEBT combined score of less than 94% of the contralateral lower extremity increased lower extremity injury odds by 6.5 in high school female athletes, and injury odds were 2.7 times more likely with greater than a 4 cm asymmetry difference with anterior reach in male and female high school athletes.17,26,35 Hegedus et al.26 also reported moderate evidence that the Single Leg Hop for Distance test can discriminate between athletes who do and do not have ankle/knee instability. Considering these previous findings, the current improvements in the mSEBT and Single Leg Hop for Distance following conditioning may indicate decreased injury risk due to gains in balance and ankle/knee stability, respectively. Despite a very small sample size, dance and
general function as indicated by the DFOS were also improved following the program, demonstrating the strong responsiveness of this new tool, which was validated recently in a larger-sample study. Continued participation in injury prevention programs throughout a season has been recommended in traditional athletics including, but not limited to, soccer. Similar independent continuation of the conditioning program may have better maintained the physical performance test improvements into the four-month follow-up period.

Previously, the utility of dance screening programs for injury prediction and prevention was questioned, mainly because standard measures from an orthopedic setting (i.e., subjective history, flexibility and strength testing) did not detect between injured and non-injured dancers and were considered too generic for this population. Similar to previous recommendations, we focused our screening on functional PPTs measuring complex interactions of movement and evaluated function with the only currently validated dance-specific subjective outcome measure. Further, dancers in this study identified their jump/landing strategies as limitations. Many indicated this was a beneficial aspect of the program, but several also recommended limiting the jump/landing focus in future conditioning programs. These findings suggest that emphasis on these strategies was meaningful, but some dancers were uncomfortable with the dosage implemented in training. Allen indicated that training for jump/landing strategy can decrease injury risk, but that too much fatigue from jumping may increase injury risk. Many of the dancers also reported that they often do not participate in cross-training as much as they would like secondary to time and money constraints. They indicated that bringing the current program to their studio and offering it without a charge increased their willingness to participate, even though it was an additional time commitment. Past researchers suggested that dance companies should be aware of and consider the financial consequences resulting from injuries. Perhaps appreciating this impact and implementing similar conditioning programs within dance company schedules may serve as a tool to decrease overall long-term costs and improve dancers’ career longevity. Financial resources are typically more readily available in larger companies, increasing their likelihood of adopting supplemental training. More overuse injuries are often found in smaller companies with limited budgets, where dancers are more frequently encouraged to dance through injury due to a lack of understudies. Perhaps adopting a sports medicine approach to preventing injuries is most important in these small companies where injuries are more prevalent. Finally, all the dancers suggested that similar conditioning programs begin at least by the pre-professional level, consistent with previous recommendations to begin with adolescent dancers.

While the first objective was analyzed thoroughly, the second and third secondary purposes could not be investigated because none of the dancers reported injury, based on the "time loss" and "modified activity" injury definitions. However, additional questioning revealed that while these dancers denied injury and reported an average 0-1/10 pain on a visual analog scale at rest, all reported between 3-6/10 average pain with activity during the study period. The data imply that the dancers consistently work through pain, and that moderate levels of pain do not necessarily signify injury to this sample. These results further support the need to develop an improved consensus definition to track injury, and suggest the need to investigate further the implications of the "dancer mentality" on pain and injury perception in dancers. Russel et al. expressed that injury risk is increased in dancers whose personalities allow them to dance through pain, and that this characteristic typically coincides with the dancer’s level of success. This thought may implicate the need for further focus on injury prevention for those dancers most likely to fill principle roles.

LIMITATIONS

This study had inherent limitations due to the self-reported nature of injury tracking with the DFOS, and the test-retest design. The within-subjects design eliminated the possibility of inferring causation from the conditioning intervention. While the study did not include a control group for comparison and evaluated relatively short-term outcomes, these design elements eliminated between-groups differences and reduced maturation bias.

The four-month follow-up was chosen to assess the dancers’ performance at the farthest period from the intervention, prior to going on a month-long holiday layoff. The authors did not want the results to be skewed due to variance in training with regards to how the dancers chose to use their vacation time. Further follow-up at the end of the season was unattainable secondary to the company touring internationally. Further follow-up beyond that time was impossible due to turnover of company dancers between seasons. The benefit of a short-term follow-up is that it reduces bias due to other training effects and can show if any short-term effects directly following the training program were no longer sustained at a relatively short-term follow-up, thus suggesting the possible need for continued performance of the conditioning program to maintain training effects. A longer follow-up period would be desirable to better determine sustainability of training effects from the program over a longer period of time. Such a follow-up would be easier attained in a larger company. For small companies such as the one studied, it is unfeasible.

Additionally, the dancers self-selected whether or not to participate, potentially causing selection bias. However, this type of selection is typical when studying such a specific population as a professional ballet company. Also, because the small sample size was possibly underpowered, the Wilcoxon signed-rank tests may not have yielded effect sizes as great as the true magnitude of change resulting from the program. Nevertheless, this limitation may not have drastically affected the results as numerous positive changes in physical performance and function following the conditioning class were demonstrated with very conservative testing.

SUGGESTIONS FOR FUTURE RESEARCH

Evaluating how a conditioning series may influence...
dancers’ short-term physical function is only the first step in determining the effectiveness of a conditioning class for reducing injury. Future research should focus on evaluating the long-term stability of balance, stability and functional improvements with and without continued conditioning, if the conditioning program physical improvements directly influence injury risk, and if the physical performance changes reported in this study may serve as mediators to injury incidence. Randomized controlled trials with larger sample sizes and reflective of a larger geographical population of dancers may improve validity and generalizability of the results, respectively.

More detailed injury tracking using injury definitions more sensitive than “time-loss”\textsuperscript{11} or “modified activity”\textsuperscript{34} may capture additional physical impairments for better testing the effects of conditioning on injury. While these are standard definitions across the current dance medicine literature, the “dancer’s mentality,”\textsuperscript{11,41,43} and the lack of a consensus definition for dance injury\textsuperscript{1,34} are well-known challenges for appropriately studying injuries in this population. Future research should focus on streamlining, validating, and possibly standardizing neuromuscular conditioning programs, with a goal of maximizing physical performance benefits and reducing injury risk in the shortest time, with the least financial resources and equipment.

CONCLUSION

Improvement in multiple PPTs and dance function were noted following the implementation of a neuromuscular conditioning program, but many of the physical gains no longer remained at a four-month follow-up. The loss in improvement at follow-up advocates the potential need for continued conditioning for maintenance of optimal physical performance. The results suggest that conditioning classes may improve professional dancers’ physical performance in areas that are related to injury risk. Subsequently, utilizing such programs may serve to decrease injury risk, but more controlled research with larger sample sizes is needed to determine if a cause-effect relationship of neuromuscular conditioning on dance function and injury exists. The results here support the previous recommendation\textsuperscript{19} that dance performance may be improved, and injury risk decreased, by applying principles of sports science to professional dancers’ training regimens.

CONFLICT OF INTEREST

The authors report no conflicts of interest.
REFERENCES


Supplementary Materials

Appendix 1

Acute Effects of Dry Needling on Myofascial Trigger Points in the Triceps Surae of Ballet Dancers: A Pilot Randomized Controlled Trial

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¹ Andrews University. ² Northwestern University

Keywords: calves, dry needling, force, range of motion, temperature, movement system

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International Journal of Sports Physical Therapy

Background

There is convincing evidence that dancers suffer injuries to the triceps surae musculature. Research on the immediate effects of dry needling (DN) is limited, and it is important to understand the acute effects of this treatment prior to performance.

Purpose

The purpose of this pilot study was to assess the immediate effects of DN on myofascial trigger points in terms of skin surface temperature, pain, active and passive range of motion, and torque production in the triceps surae of ballet dancers.

Study Design

Randomized, double-blinded pilot study

Methods

Professional ballet dancers that fit inclusion and exclusion criteria (n=11) were randomly assigned to an experimental or control group. The dancers had three pre-determined standard point (SP) measurement spots that were used as a baseline for surface temperature comparisons. The dancers were also palpated for trigger point (TP) spots. Both SP and TP spots were marked for future measurements. The experimental group received DN, while the control group received sham DN (SHAM) to their bilateral calves at the TP spots. Immediately prior to and following treatment, both DN and SHAM groups were tested for skin surface temperature, pain, range of motion, and plantar flexion torque by blinded assessors. Paired t-tests and independent t-tests were performed to examine differences between groups.

Results

The surface temperature for the TP was higher than the SP measurements prior to intervention (Right calf p=.014; Left calf p=.031). There were no significant changes in VAS scale reported pain and ROM. The plantar flexion torque measurements showed an increase in the DN group of the left calf at the angular velocity of 60 degrees/sec.

Conclusion

This was a unique pilot study examining the acute effects of DN on professional ballet dancers. The results were limited due to low sample size. However, the methodology for this study and surface temperature results invites future research.

Level of evidence

Level 1b
INTRODUCTION

Dancers often suffer from decreased ability to perform relevé, plié, and jumping due to deficits at the ankle joint.¹ ² Calf pain from overuse, prevalent among professional ballet dancers, creates these limitations, which prevents the dancer from performing at their full potential.³–⁵ Research suggests dry needling (DN) may be effective for immediately decreasing musculoskeletal pain,⁶–¹⁷ but the acute results of DN on range of motion (ROM) have been mixed.⁷,⁸,¹⁰,¹²,¹⁴,¹⁶,¹⁸,¹⁹ Currently, evidence regarding the immediate results of DN on gastrocnemius and soleus function is limited.¹⁴ Additionally, only a small number of studies have demonstrated the instant effects of DN on force production.²⁰–²² There are no studies on DN and surface temperature of the specific muscle treated.

Myofascial pain occurs in patients with MTrPs, defined as a point within a taut skeletal muscle exhibiting an increased response to a stimulus.²³ One hypothesis for the cause of MTrPs is that acetylcholine (ACh) is released excessively at the neuromuscular junction, creating an area of tautness within the muscle.²⁵ This may cause unrelenting stimulation of the sarcomere and may lead to hypoxia.²³–²⁵ DN involves the insertion of a thin, filiform needle into MTrPs that elicit a local twitch response affecting the ACh at the neuromuscular junction.²⁵ DN is also thought to impact blood flow by causing the release of vasoactive substances, which promote vasodilation and increase oxygenation similar to deep tissue massage.²³,²⁶,²⁷

Even though researchers have documented increases in blood flow and oxygen saturation to the tissue after DN, the question remains if DN affects the surface temperature at the tissue being treated.²³,²⁶,²⁸,²⁹ One study demonstrated an increased temperature reading at an acupuncture point after the needle was in this point for 10 minutes.³⁰ Recent research has shown that DN provokes intense vasodilation and temperature increases in measured referral points to the muscle treated.³¹ However, there are no studies that assess the pre- and post-surface temperature of the specific muscle being treated with DN.

Meta-analyses conducted on pain scores indicate that there is a statistically significant improvement in pain ratings immediately after DN.⁹,³² DN has also been shown to reduce pain faster than analgesics following total knee arthroplasty.¹⁵ Instant improvement on pain pressure threshold in the masseter muscle compared to placebo, decreased pain sensitivity in 57 shoulder patients, and a decrease in cervical muscular pain have been demonstrated after DN.⁶,⁸,¹²,¹³ Patients with myofascial pain syndrome demonstrated improvements on the Visual Analog Scale (VAS) after DN vs. sham needles immediately and at four weeks post treatment.¹⁷

Other authors have explored the effects of DN on pain in athletes such as rugby and volleyball.¹⁰,¹⁴,¹⁶,¹⁸ Mason, Tansey and Westrick reported decreased knee pain after DN in a case report on a dancer with posterior knee pain.¹⁴ These results on athletes might indicate DN as an effective means to treat ballet dancers’ calf pain immediately, but DN’s impact on performance ability remains unclear.

Amongst dancers, the effect of DN on ROM is especially important. Since one-fourth of injuries in ballet dancers involve the ankle joint, improving dorsiflexion ROM is key to prevention and treatment of acute and overuse injuries.⁴ Adequate triceps surae flexibility has demonstrated increased dorsiflexion ROM, increased force production by improving the ability to generate elastic energy, and decreased excessive pronation upon weight acceptance.⁴,³⁵ In addition, increased dorsiflexion when landing jumps has been suggested to increase ankle plantar flexor pre-stretch, which may improve the utilization of elastic energy and enhance jump function.³⁴ Therefore, improving dorsiflexion ROM of the triceps surae may be important in injury prevention and dancer performance.

Fernandez-De-Las-Penas describes trigger points as taut bands which limit joint mobility.³⁵ Grievé et al³⁶,³⁷ performed studies on manual trigger point release to the triceps surae musculature and reported positive results in regards to ROM after intervention. Eftekharzadat, Babaei-Ghazani, and Zeinolabedinzadeh³⁸ performed DN in patients with heel pain and demonstrated no effect in ankle ROM. However, the methodology of this study was different because it pre-determined points in the calf, did not manipulate the needle, and the measurements were taken at 4 weeks post-intervention.³⁸ Additional authors have found immediate increases in shoulder ROM,¹⁶,³⁹ cervical ROM,⁷,¹²,¹⁸,⁴⁰ and jaw opening³ after DN.

Due to the possibility of increased ROM, DN may impact force and torque production immediately after treatment. Behm and Chaouachi¹ have shown that increased ROM is associated with decreased force production acutely.¹ Prolonged static stretching, which also increases ROM, has been shown to decrease voluntary peak torque and electromyographic amplitude when subjects perform isometric maximal voluntary contractions.⁴¹ Static stretching causes decreased strength production by affecting the length-tension relationship of the muscle secondary to changes in compliance.¹ If DN could have the same lengthening effects as stretching, it may also have a similar potentially detrimental effect on torque production.

However, Ge²¹ found that latent trigger points decrease force production, so it is vital to research the effect DN would have on force production. Dar and Hicks found²⁰ that DN in multifidus increases muscle function immediately. Cerezo-Telléz et al demonstrated an immediate cervical muscle strength in all directions of flexion, extension, rotation, and side bending after cervical DN.⁷ DN has improved muscle endurance of the knee extensors immediately and at four weeks in soccer players.²²

DN might not result in improved outcomes immediately. Huguenin et al¹⁰ found that pain improved with DN, but passive straight leg raise and hip internal rotation remained unchanged in both therapeutic dry needling and placebo groups. However, Huguenin et al¹⁰ also concluded that they did not chose the appropriate ROM assessment. One RCT of DN demonstrated no improvement in hamstring ROM or knee pain immediately when compared to sham DN.⁴² One meta-analysis states that DN is less effective in treating pain conditions, but may be better at increasing ROM.¹⁹ DN has been demonstrated as less effective than acupunc- ture for motion-related chronic neck pain.⁴³

The purpose of this study was to assess the immediate effects of DN on myofascial trigger points in terms of skin...
Methods
Subjects
Eleven healthy, full time (25 hours of dance per week) ballet dancers were recruited from a professional ballet company by word of mouth. These dancers were included in the study if they presented with MTrPs in the calf through palpation. Dancers were excluded if they had significant health problems or bleeding disorders, were pregnant, feared needles, or had taken anticoagulant or pain relieving medications within the past 24 hours. Participation in this study was also denied if an individual had undergone DN or acupuncture in the prior four weeks. Prior to testing, the participants read and signed a specific Northwestern University and Andrews University IRB approved consent form. This included a health history form asking about recent injuries and general medical health.

Subjects were randomly assigned into two groups through computerized random number generation by the physical therapist performing the intervention so the assessors were blinded. The experimental group received bilateral DN to the calf, plus passive calf stretching of two repetitions of thirty seconds on a slant board in both knees bent and straight positioning, while the control group received bilateral sham DN (SHAM) in addition to the same slant board calf stretching protocol. All subjects had the intervention performed in a lab room at Northwestern University’s Physical Therapy department. A physical therapist provided the intervention, while physical therapy students, blinded to group assignment, obtained pre/post measurements after they had practiced and demonstrated competency in their measurement areas.

Materials
DN was performed using Seirin J-Type 30x30 needles. The 10cm VAS (Visual Analog Scale) was used to assess overall calf pain pre- and post- intervention as reported by participant, and temperature was measured with The Exergen TAT-2000 Series Professional Model Temporal Scanner (Exergen Corporation, Watertown, MA). A goniometer was used to measure the ankle dorsiflexion PROM in CKC (closed kinetic chain) and AROM in OKC (open kinetic chain). An isokinetic dynamometer, the Biodex System 3 Pro (Biodex Medical Systems, Shirley, New York), was used to measure calf force.

Procedure
Individuals meeting inclusion criteria were randomly blinded and placed into either the experimental or control group. The subjects were barefoot and wore athletic clothing. Each dancer followed a five-minute, standardized dance-specific warm up video prior to testing.

Initially, baseline skin temperature was measured at three standard points (SP) with a surface thermometer placed on marked spots 10cm below the popliteal fold, 10cm above the calcaneal tuberosity, and at a point in between. A blinded assessor performed and averaged the three measurements to discern an overall calf temperature pre-intervention. Then, a physical therapist certified in DN and having >10-years’ experience palpating dancers’ calf musculature located five trigger point (TP) spots using palpation. The trigger points were circled with a marker (Figure 1).

After trigger point palpation, another blinded assessor administered a 10cm Visual Analog Scale (VAS) for the overall pain score of the five TP pre-intervention. The same blinded assessor measured all of the subjective calf pain for both the DN and SHAM groups pre- and post-intervention. The blinded assessor used the same script for each subject. The VAS has established test-retest reliability and sensitivity, and change in pain intensity can be easily obtained. A 50% pain reduction measured by the VAS was determined as statistically significant. As demonstrated in previous research, participants had access to their pre-test VAS at the time of the post-test VAS to reduce error.

Next, the original temperature assessor measured surface temperature one more time to the nearest degree (Fahrenheit) at the marked TP and SP locations. The five TP measurements were averaged and the three SP measurements were averaged. This set of surface temperature measures was performed post-palpation, but pre-intervention, to confirm that the physical therapist’s palpation did not affect surface temperature. This second round of SP surface temperature measurements was conducted to confirm that...
the calf palpation did not change baseline temperature.

Ankle dorsiflexion AROM was measured bilaterally by a single blinded assessor using a standard 6-inch goniometer with the subjects in an open-kinetic chain seated position and for PROM in the closed-kinetic chain (CKC) weight-bearing lunge position. In OKC, the subjects sat over the edge of a plinth with their knees bent approximately 45-60° in order to prevent passive insufficiency of the gastrocnemius. The subtalar joint was placed in neutral position with the transcondylar axis of the knee in the frontal plane. Ankle dorsiflexion active range of motion (AROM) was measured in open chain first, using the standard text version. The neutral position was 0° and ankle motion was recorded to the nearest degree from that position in the dorsal direction. Subjects were asked to perform maximal active ankle dorsiflexion bilaterally three times and the angle was measured to the nearest degree. All measurements were recorded and the mean of the three was used for analysis. Only AROM was measured in this position because it is more functional and applicable to ballet while passive ROM could be influenced by human error due to the inconsistency with overpressure.

Dickson et al found that functional ankle dorsiflexion in modern dancers is best quantified in the weight-bearing lunge position, which has also been previously assessed for intra-rater (ICC=0.97-0.98) and inter-rater (ICC= 0.97-0.99) reliability. Subjects were asked to stand facing a wall in a lunge position with one knee touching the wall and the foot on the same lower extremity sliding backward to the point of maximum tolerance while the knee remains in contact with the wall and the heel with the floor. Researchers verified that each subject’s knee and heel remained in contact with the appropriate surface, and that the knee was aligned over the second toe prior to taking any measurements. The same bony landmarks were used to align the goniometer as in OKC ankle dorsiflexion AROM. Measurements were recorded three times bilaterally and the mean of the three was used for analysis. (Figure 2)

Maximum muscular torque of the triceps surae was measured bilaterally using a Biodex prior to and after the DN or SHAM intervention. Two assessors blinded to group assignment performed all of these measurements. The participants were barefoot, seated and secured using a double chest strap, quadriceps strap, and two additional support straps fastened over the dorsum of the foot. The hip was placed at 90° flexion, the knee at 30° flexion, and the ankle at an angle of comfort for the participant. The axis of rotation of the Biodex ankle attachment was aligned with the lateral malleolus of the ankle being tested. Prior to testing, the participants warmed up by submaximally plantar- and dorsiflexing each ankle ten times on the Biodex with no resistance. The subject then performed four maximal concentric contractions plantar flexion at angular velocities of 60°, 90°, and 120°/sec with a two-minute rest period between tests to minimize fatigue. The order of velocities was randomized. The first measurement was eliminated, and the remaining three were averaged for analysis using standard Biodex software in Newton.meters (NM).32,46,49 (Figure 3).

After all the pre-tests, the DN was administered to participants in the experimental group, while the control group received SHAM dry needling while lying prone on a plinth. The assessors were not present during the DN or sham DN. The DN was performed in the five previously palpated and circled trigger point locations on each calf using a clean technique with sterile needles. Needles were inserted into the triceps surae and repeatedly moved up and down in order to elicit a twitch response. All DN participants had twitch responses during the DN intervention.

The sham needles were prepared following the method adopted by Cotchett et al,50 which was originally found to be valid by Tough and colleagues. Prior to treatment, the needle tips were removed with wire cutters. The end of the needle was filed down to create a blunt surface that when tapped would not pierce the skin. The sham needle was placed back into its tube and repackaged. To begin each
treatment, the skin was disinfected and a prepared sham needle was removed from packaging to stimulate a removal of a real needle.\textsuperscript{52} The sham needle was manipulated using the same technique as real dry needling. First, the applicator was placed on the skin and the dry needling administrator tapped the needle without piercing the skin. The applicator was removed while the administrator held the sham needle in place on the skin’s surface and mimicked needle rotation for five seconds, then removed the needle. The sham needle was disposed of in a sharps container to simulate the noise and effects associated with sharps disposal.\textsuperscript{50}

Following the intervention, both groups were instructed to stretch on a 20° incline slant-board with straight and bent knees twice for 30 seconds. The choice to stretch after DN or SHAM as part of an intervention was to mimic the common tendency of ballet dancers to stretch after clinical treatment. Immediately following stretching, pain, temperature, ROM and torque were re-measured on both sides.

At the end of the procedures, the participants were debriefed on their treatment and given a contact number to call if they had any further questions or report adverse effects. No adverse effects were reported. Participants in the control group were given the opportunity to receive dry needling once they had completed the experiment but all declined. A summary of the methodology can be found in Figure 4.

DATA ANALYSIS

The raw data collected was used to calculate the independent and dependent variables. SPSS Version 10.0 (SPSS Inc, Chicago, IL) was used to analyze this data. A paired t-test was performed to compare pre- and post-intervention, as well as independent t-test to compare between the two test groups using a 95% confidence interval. Additionally, non-parametric statistics were run and the outcomes where statistically significant differences were found were the same between nonparametric and parametric analyses. Because of the specific homogenous population, parametric statistics were chosen. A histogram analysis looking for equally distributed variables was also performed. Statistical differences were assessed using the value \( p<0.05 \).

RESULTS

Six male and five female professional ballet dancers from
Table 1: Demographic data

<table>
<thead>
<tr>
<th>SUBJECT NUMBER</th>
<th>GENDER</th>
<th>YEARS PROFESSIONAL DANCING</th>
<th>PRIOR DRY NEEDLING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>12</td>
<td>YES</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>3</td>
<td>NO</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>6</td>
<td>YES</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>3</td>
<td>NO</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>6</td>
<td>YES</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>12</td>
<td>NO</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>15</td>
<td>YES</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>13</td>
<td>NO</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>15</td>
<td>NO</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>17</td>
<td>YES</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>4</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 2: Comparison of means (± SD) between right and left sides of dancers prior to intervention

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT DATA</th>
<th>LEFT DATA</th>
<th>p-value (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger point surface temperature</td>
<td>96.9± .42</td>
<td>96.76± .54</td>
<td>.187</td>
</tr>
<tr>
<td>VAS pain score</td>
<td>4.38± 1.942</td>
<td>4.17± 1.344</td>
<td>.759</td>
</tr>
<tr>
<td>OKC Sitting ROM</td>
<td>11.36±4.73</td>
<td>10.51±3.93</td>
<td>.420</td>
</tr>
<tr>
<td>CKC Lunge ROM</td>
<td>29.03±5.133</td>
<td>29.60±4.89</td>
<td>.620</td>
</tr>
<tr>
<td>Torque at 60 degrees/sec</td>
<td>36.79±10.53</td>
<td>35.47±11.66</td>
<td>.570</td>
</tr>
<tr>
<td>Torque at 90 degrees/sec</td>
<td>34.04±11.24</td>
<td>36.64±12.15</td>
<td>.378</td>
</tr>
<tr>
<td>Torque at 120 degrees/sec</td>
<td>34.22±8.47</td>
<td>34.22±11.85</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The same professional ballet company fit the inclusion/exclusion criteria. The average number of years dancing professionally was 9.6. Six out of eleven of the dancers had used DN prior to the study. This was a uniform sample, as the subjects were similar in age and from the same professional ballet company. Males and females were similarly represented in both groups. (Table 1)

The mean measurements of pain, temperature, ROM and torque were calculated for all subjects prior to intervention. There were no significant differences for any mean measurement comparing right and left calves in temperature, pain, ROM, or force prior to the intervention. (Table 2)

TEMPERATURE

Prior to intervention, the mean surface temperature of the TP measurements was higher than the SP measurements when performing an independent t-test. This statistical significance happened in both the right and left calves (right: p= .014; left: p=.051). (Table 3) Using a paired t-test, the mean temperature for both the right and left calves in the SHAM group (right: p=.008; left: p=.008) and only the right calf in the DN group (right: p=.048) showed significance in temperature decrease from pre- to post- intervention. (Table 4)

VAS

There were no significant differences in mean VAS reported pain scores for either the SHAM or DN groups pre- to post-intervention. (Table 5)

ROM

In the seated AROM dorsiflexion measurement, the SHAM group had a statistically significant larger change in mean values in only the left calf (left: p=.005) when compared to the DN group. However, when a paired t-test compared the pre- and post- intervention measurements of the seated AROM dorsiflexion measurement in the SHAM group on the left calf, there was no statistical significance. (Table 6)

There was no significant difference in the lunge CKC measurement of dorsiflexion between the DN to the SHAM group. (Table 7)

BIODEX TORQUE

There was a statistically significant (p=.027) increase in the torque of the plantar flexors at the 60-degree angular velocity (Table 8) in the DN group left side only when pre- and post- intervention was compared with a paired t-test.
Table 3: Mean temperature of three standard points (SP) calf measurements, reported in degrees, and statistical comparisons

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT SIDE DATA</th>
<th>LEFT SIDE DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP pre/post palpation</td>
<td>Pre-palp: 95.51±1.74</td>
<td>Pre-palp: 95.32±1.86</td>
</tr>
<tr>
<td></td>
<td>Post-palp: 96.06±1.07</td>
<td>Post-palp: 95.72±1.57</td>
</tr>
<tr>
<td></td>
<td>(t(10)= -1.77, p=.107, 2-tailed)</td>
<td>(t(10)= -1.50, p=.164, 2-tailed)</td>
</tr>
<tr>
<td>SP initial palpation compared to 3 standard points post DN</td>
<td>Post-palp: 95.82±1.37</td>
<td>Post-palp: 95.82±1.32</td>
</tr>
<tr>
<td></td>
<td>Post-DN: 94.99±1.73</td>
<td>Post-DN: 95.39±1.09</td>
</tr>
<tr>
<td></td>
<td>(t(5)= -.898, p=.410, 2-tailed)</td>
<td>(t(5)= -.582, p=.586,2-tailed)</td>
</tr>
<tr>
<td>SP post initial palpation compared to SP post SHAM intervention</td>
<td>Post-palp: 96.35±.57</td>
<td>Post-palp: 95.61±1.98</td>
</tr>
<tr>
<td></td>
<td>Post-SHAM 95.89±.33</td>
<td>Post-SHAM: 95.51±.68</td>
</tr>
<tr>
<td></td>
<td>(t(4)= 2.50, p=.067.2-tailed)</td>
<td>(t(4)= 1.50, p=.888, 2-tailed)</td>
</tr>
<tr>
<td>Temperature difference of SP pre/post intervention, comparing DN and SHAM</td>
<td>Change DN: 1.18±1.42</td>
<td>Change DN: 1.19±1.17</td>
</tr>
<tr>
<td></td>
<td>Change SHAM: 47.± .39</td>
<td>Change SHAM: 1.07± .83</td>
</tr>
<tr>
<td></td>
<td>(t(9)=.0.20, p=.075, 2-tailed)</td>
<td>(t(9)=.342, p=.740,2-tailed)</td>
</tr>
<tr>
<td></td>
<td>Equal variances assumed</td>
<td>Levene’s significance= .000</td>
</tr>
<tr>
<td></td>
<td>Levene’s significance= .176</td>
<td></td>
</tr>
<tr>
<td>SP compared to trigger points (TP) post palpation and prior to intervention</td>
<td>SP: 96.06±1.07</td>
<td>SP: 95.72±1.57</td>
</tr>
<tr>
<td></td>
<td>TP: 96.88±.43</td>
<td>TP: 96.76±.55</td>
</tr>
<tr>
<td></td>
<td>(t(10)= -2.96, p=.014.2-tailed)</td>
<td>(t(10)= -2.52, p=.031, 2-tailed)</td>
</tr>
</tbody>
</table>

*Bold indicates significant difference*

Table 4: Mean temperature of five trigger points (TP) calf measurements, reported in degrees with DN or SHAM and statistical comparisons

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT SIDE DATA</th>
<th>LEFT SIDE DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP pre and post DN</td>
<td>Pre-DN: 96.86 ± .23</td>
<td>Pre-DN: 96.72 ± .45</td>
</tr>
<tr>
<td></td>
<td>Post-DN: 96.51±.32</td>
<td>Post-DN: 96.35 ± .41</td>
</tr>
<tr>
<td></td>
<td>(t(5)=2.61, p=.0482,2-tailed)</td>
<td>(t(5)=2.03, p=.098, 2-tailed)</td>
</tr>
<tr>
<td>TP pre and post SHAM</td>
<td>Pre-SHAM 96.92, ± .62</td>
<td>Pre-SHAM 96.81 ± .70</td>
</tr>
<tr>
<td></td>
<td>Post-SHAM 96.17±.33</td>
<td>Post-SHAM 95.97 ± .47</td>
</tr>
<tr>
<td></td>
<td>(t(4)=4.92, p=.0082,2-tailed)</td>
<td>(t(4)=4.92, p=.0082,2-tailed)</td>
</tr>
<tr>
<td>Temperature difference of TP comparing DN and SHAM</td>
<td>Change DN: .41, ± .21</td>
<td>Change DN: .48, ± .30</td>
</tr>
<tr>
<td></td>
<td>Change SHAM: .74, ±.34</td>
<td>Change SHAM: .83, ± .38</td>
</tr>
<tr>
<td></td>
<td>(t(9)=.1.99, p=.077, 2-tailed)</td>
<td>(t(9)=.1.74, p=.116, 2-tailed)</td>
</tr>
<tr>
<td></td>
<td>Equal variances assumed</td>
<td>Equal variances assumed</td>
</tr>
<tr>
<td></td>
<td>Levene’s significance= .474</td>
<td>Levene’s significance= .473</td>
</tr>
</tbody>
</table>

*Bold indicates significant difference*

Table 5: Mean visual analog pain scale score, in centimeters

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT DATA</th>
<th>LEFT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre and Post DN</td>
<td>Pre-DN: 4.03±1.10</td>
<td>Pre-DN: 4.33±1.06</td>
</tr>
<tr>
<td></td>
<td>Post-DN: 3.38±1.68</td>
<td>Post-DN: 3.69±1.95</td>
</tr>
<tr>
<td></td>
<td>(t(5)=1.32, p=.246,2-tailed)</td>
<td>(t(5)=1.69, p=.533, 2-tailed)</td>
</tr>
<tr>
<td>Pre and Post SHAM</td>
<td>Pre-SHAM 4.80±2.74</td>
<td>Pre-SHAM 3.99±1.74</td>
</tr>
<tr>
<td></td>
<td>Post-SHAM 4.58±2.74</td>
<td>Post-SHAM 3.95±1.34</td>
</tr>
<tr>
<td></td>
<td>(t(4)=.242, p=.821, 2-tailed)</td>
<td>(t(4)=.040, p=.970, 2-tailed)</td>
</tr>
<tr>
<td>Change of VAS score, comparing DN and SHAM DN</td>
<td>Change DN: 958±.906</td>
<td>Change DN: 1.63±1.63</td>
</tr>
<tr>
<td></td>
<td>Change SHAM: 1.44±1.27</td>
<td>Change SHAM: 1.94± .591</td>
</tr>
<tr>
<td></td>
<td>(t(9)= -.735, p=.481,2-tailed)</td>
<td>(t(9)= -.396, p=.701, 2-tailed)</td>
</tr>
<tr>
<td></td>
<td>Equal variances assumed</td>
<td>Equal variances assumed</td>
</tr>
<tr>
<td></td>
<td>Levene’s significance= .435</td>
<td>Levene’s significance= .083</td>
</tr>
</tbody>
</table>

*Bold indicates significant difference*

In the 90 and 120-degree angular velocity (Table 2 and 10), there was a statistically significant difference at 90 degrees (p = .014) and 120 degrees (p = .001) noted for mean change in torque, when comparing DN and SHAM on the right side.
Table 6: Mean OKC dorsiflexion ROM (AROM), measured in a seated position, reported in degrees

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT DATA</th>
<th>LEFT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre and Post DN</td>
<td>Pre-DN: 11.28±5.09</td>
<td>Pre-DN: 11.05±3.48</td>
</tr>
<tr>
<td></td>
<td>Post-DN 12.11±1.49</td>
<td>Post-DN 10.28±3.64</td>
</tr>
<tr>
<td></td>
<td>(t(5)= -.503, p=.636, 2-tailed)</td>
<td>(t(5)=1.94, p=.110, 2-tailed)</td>
</tr>
<tr>
<td>Pre and Post SHAM</td>
<td>Pre-SHAM 11.46±4.84</td>
<td>Pre-SHAM 9.87±4.77</td>
</tr>
<tr>
<td></td>
<td>Post-SHAM 11.60±7.46</td>
<td>Post-SHAM 9.73±5.90</td>
</tr>
<tr>
<td></td>
<td>(t(4)= -.088, p=.934,2-tailed)</td>
<td>(t(4)=.076, p=.943,2-tailed)</td>
</tr>
<tr>
<td>Change in Dorsiflexion, Comparing DN</td>
<td>SHAM: 2.61±3.03</td>
<td>Change DN: 2.11±1.13</td>
</tr>
<tr>
<td>and SHAM</td>
<td>(t(9)= -2.11, p=.039, 2-tailed)</td>
<td>Change SHAM: 3.33±1.33 (t(9)= -3.66, p=.005, 2-tailed)</td>
</tr>
<tr>
<td></td>
<td>Equal variances assumed</td>
<td>Equal variances assumed</td>
</tr>
<tr>
<td></td>
<td>Levene's significance: .399</td>
<td>Levene's significance: .425</td>
</tr>
</tbody>
</table>

Table 7: Mean CKC dorsiflexion ROM (PROM), measured during the lunge, reported in degrees

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT DATA</th>
<th>LEFT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre and Post DN</td>
<td>Pre-DN: 28.22±5.26</td>
<td>Pre-DN: 29.05±4.98</td>
</tr>
<tr>
<td></td>
<td>Post-DN: 29.89±3.99</td>
<td>Post-DN 28.28±3.68</td>
</tr>
<tr>
<td></td>
<td>(t(5)= -1.58, p=.175, 2-tailed)</td>
<td>(t(5)= -1.62, p=.557, 2-tailed)</td>
</tr>
<tr>
<td>Pre and Post SHAM</td>
<td>Pre-SHAM: 30.00±5.40</td>
<td>Pre-SHAM: 30.27±5.26</td>
</tr>
<tr>
<td></td>
<td>Post-SHAM: 32.80±4.58</td>
<td>Post-SHAM: 31.60±2.52</td>
</tr>
<tr>
<td></td>
<td>(t(4)= -1.26, p=.277, 2-tailed)</td>
<td>(t(4)= -.952, p=.395, 2-tailed)</td>
</tr>
<tr>
<td>Change in Dorsiflexion, Comparing DN</td>
<td>Change DN: 1.67±2.59</td>
<td>Change DN: 2.11±2.13</td>
</tr>
<tr>
<td>and SHAM</td>
<td>Change SHAM: 4.67±2.71</td>
<td>Change SHAM: 2.40±2.19</td>
</tr>
<tr>
<td></td>
<td>(t(9)= -.88, p=.093, 2-tailed)</td>
<td>(t(9)= -.222, p=.829, 2-tailed)</td>
</tr>
<tr>
<td></td>
<td>Equal variances assumed</td>
<td>Equal variances assumed</td>
</tr>
<tr>
<td></td>
<td>Levene's significance: .008</td>
<td>Levene's significance: .006</td>
</tr>
</tbody>
</table>

Table 8: Mean Biodex triceps surae torque in Newton.Meters at angular velocity 60 degrees/sec

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>RIGHT DATA</th>
<th>LEFT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE and POST DN</td>
<td>Pre-DN: 38.87±8.47</td>
<td>Pre-DN: 35.61±6.26</td>
</tr>
<tr>
<td></td>
<td>Post-DN: 45.09±10.80</td>
<td>Post-DN 43.20±8.96</td>
</tr>
<tr>
<td></td>
<td>(t(5)= -2.26, p=.073, 2-tailed)</td>
<td>(t(5)= -.309, p=.027, 2-tailed)</td>
</tr>
<tr>
<td>PRE and POST SHAM</td>
<td>Pre-SHAM: 34.29±13.17</td>
<td>Pre-SHAM: 35.31±17.05</td>
</tr>
<tr>
<td></td>
<td>Post-SHAM: 40.83±14.37</td>
<td>Post-SHAM: 45.03±19.55</td>
</tr>
<tr>
<td></td>
<td>(t(4)= -1.97, p=.121, 2-tailed)</td>
<td>(t(4)= -.155, p=.197, 2-tailed)</td>
</tr>
<tr>
<td>Change in Torque, Comparing DN to SHAM</td>
<td>Change DN: 7.23±5.40</td>
<td>Change DN: 6.86±5.85</td>
</tr>
<tr>
<td></td>
<td>Change SHAM: 8.19±4.97</td>
<td>Change SHAM: 23.76±8.90</td>
</tr>
<tr>
<td></td>
<td>(t(9)= -.304, p=.768, 2-tailed)</td>
<td>(t(9)= -.255, p=.156, 2-tailed)</td>
</tr>
<tr>
<td></td>
<td>Equal variances assumed</td>
<td>Equal variances assumed</td>
</tr>
<tr>
<td></td>
<td>Levene's significance: .607</td>
<td>Levene's significance: .478</td>
</tr>
</tbody>
</table>

**Bold** indicates significant difference.

only. The SHAM group had a larger mean change than the DN group. This change in the SHAM group was an increase in torque, but it was not statistically significant when comparing pre/post intervention measurements for the 90 and 120-degree angular velocity using a paired t-test.

**DISCUSSION**

Baseline measurements of surface temperature, pain, ROM, and torque demonstrated no significant difference between the right and left sides prior to intervention. (Table 2) This is interesting because dancers often have a lateral preference when performing, but this was not seen in the current measurements.11 This is relevant to future studies in dry needling because it demonstrates that perhaps only one side is needed for measurements and intervention.

Surface temperature measurements pre-intervention showed significantly lower SP mean temperature as compared to the TP mean temperature for the right and left sides (p=.014 right, p=.013 left). After intervention, both
the right and left calves in the SHAM group, and right calf in the DN group showed a significant difference in mean temperature. The only other study that measured surface temperature with trigger points and dry needling was Skorupska et al,31 and they noticed an increase in surface temperature in muscles distal to the muscle being treated along the same nerve distribution after DN. A larger sample size would continue to investigate temperature responses after dry needling, since current research remains inconclusive in the direction of temperature change.

30,31 The surface temperature findings are important in that it invites new research because demonstrates a potential nature of trigger point changes that may occur to MTrPs after DN. The baseline surface temperature is also important knowledge for the researchers that are trying to further understand trigger point physiology.

There were no significant findings for changes in pain which differs from the results of other investigations who demonstrated decreased pain after DN.9–17 Perhaps, specific population interprets pain differently, despite having used the uniform script to describe pain. Tajet-Foxell and Rose53 found that dancers had a higher pain threshold in regards to duration of pain but not intensity on a cold pain tolerance test. Due to this, dancers might tolerate the palpation of the trigger points but might rank the post DN palpation of the tender points as higher on a VAS, delineating the results differently than a typical population. Additionally, the examiner asked the subjects to average the pain between all five trigger points. A suggestion for future research would be to have the subjects rank each spot individually for pain, and then calculate a mean measurement. Lastly, immediate post-needling muscle soreness may have contributed to VAS outcomes, as Ziaeifar et al54 suggested that their subjects had improved pain intensity after two days instead of immediately after DN of the upper trapezius muscle.

The results of current research varies with trends in increases or decreases in ROM after immediate DN.7,8,10,12,14,16,18 For seated AROM, the SHAM group had a statistically larger change in AROM pre/post intervention on the left side (p = .005) as compared to the DN group. The lunge PROM measurements had no statistical difference between the DN and SHAM groups. Since this measure was performed in self-controlled lunging, some of dancers in the DN group might have been sore from the intervention and therefore self-limited their passive motion. Further research with a larger sample size needs to be performed as this study was underpowered, because our power analysis for ROM measurements required a sample size of 48 subjects.

In the 60-degree angular velocity Biodex force, the DN group on the left side only showed a statistically significant
increase in torque production. In both the 90 and 120-degree angular velocity tests, the SHAM group had a statistically significant change as compared to the DN group on the right side only, but this was not significant when comparing pre/post intervention measures. To date, there are no known studies that compare DN using measurements of plantar flexion torque immediately after intervention. Since these findings are limited by the size of the study, caution should be used when performing DN prior to dance performance. Further research into the immediate effects on plantar flexion torque should be conducted.

There are several limiting factors in this study. As previously mentioned, this study was underpowered, which may have resulted in Type II errors. In part, this was due to coordinating multiple assessors in addition to the research process requiring 90 minutes per subject. Additionally, some subjects had previous experience with DN and were familiar with the twitch response. This potentially allowed them the ability to guess which treatment group they were assigned to, therefore limiting the subject-related blinding. Two subjects requested to not be dry needled due to concerns of being sore for dance rehearsal, so the SHAM group had two non-blinded subjects, further impacting the validity of the blinded subjects’ results.

This pilot study builds the framework for future DN studies, but further research is needed to determine the appropriate instruments to measure the effects of DN in the dance population. The unique methodology used in this study is important to consider when exploring further DN research. The assessors were blinded, reducing rater bias. All assessors were trained physical therapy students, and the same assessor took all measurements. Additionally, this pilot studied used a sham intervention to further blind the subjects.

CONCLUSION

The results of this research were inconclusive for changes in surface temperature, pain, ROM, and torque immediately after dry needling to the triceps surae musculature. However, this is the first blinded and randomized controlled study assessing the acute effects of DN in professional ballet dancers with a novel methodology for conducting further research. This study also presents potential information on the surface temperature of trigger points as compared to baseline temperature measurements. Further research is needed with larger sample sizes in order to fully understand the immediate effects of dry needling in the dance population prior to performance.

STATEMENT OF INSTITUTIONAL BOARD
Northwestern University, Chicago, IL STU00096692

CONFLICTS OF INTEREST
The authors report no conflicts of interest.

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REFERENCES


Background
With the increased popularity of foam rolling (FR), it is important to establish the exact manner in which the practice is useful.

Purpose
The purpose of this study was to examine the impact of FR the iliotibial (IT) band on hip adduction range of motion (ROM) and the short-term time course of any ROM changes that may occur.

Method
In a within-subject design, 34 subjects (21 female, 13 male) (female mean age 24.67 ± 8.6 yrs, height 161.4 ± 9.8 cm, mass 67.3 ± 12.3 kg; male mean age 22 ± 2.5 yrs, height 170.2 ± 8.2 cm, mass 76.3 ± 21.9 kg) underwent a baseline Ober's test to measure hip adduction ROM prior to the FR and control conditions. Subjects rolled the lateral portion of each thigh for 3 bouts of 20 seconds. A tempo of 3 seconds down and 3 seconds up the leg was maintained across FR bouts. A 5-minute walk served as the control condition. The Ober's test was repeated at less than 1 minute, 3 minutes, 10 minutes, 15 minutes, and 20 minutes following the FR bouts and the control to assess changes in hip adduction ROM over time. A blinded clinician conducted the Ober’s test. A two-way analysis of variance was used to assess differences by condition and time.

Results
No differences in hip adduction ROM were found at baseline between FR and CON within subjects (27.9 cm ± 7.5 vs. 27.7 cm ± 6.6, p > .05). Ober’s test ROM was significantly greater in FR compared to CON immediately post-treatment (24.2 cm ± 6.3 vs. 28.2 cm ± 6.3, p = .00, d = .59), and 3 minutes post (24.6 cm ± 7.6 vs. 28.3 cm ± 5.9, p = .00, d = .56). No differences were observed 10 minutes post, 15 minutes post, or 20 minutes post FR or CON (p > .05).

Discussion
Compared to walking, FR the IT band significantly increased hip adduction ROM as measured by the Ober’s test. These increases appear to dissipate between 3 and 10 minutes post-FR.

Conclusion
An acute bout of 3 sets of 20 seconds of FR may be effective for transiently increasing ROM. Whether these short-term increases have implications for chronic flexibility changes is unclear.

Level of evidence
2
INTRODUCTION

Foam rolling (FR) is an increasingly popular practice shown to improve range of motion (ROM) without concomitant decreases in strength and power.\(^1,2\) It is also thought to accelerate recovery from exercise-induced muscle damage.\(^2,3\) Foam rolling is commonly applied in therapeutic settings, with a purported benefit towards various soft tissue-based pathologies, though evidence supporting the use of FR for this purpose is limited.\(^4\)

Investigations concerning FR’s influence on acute flexibility changes typically report increases in between 4% and 16%.\(^2\) While these increases are smaller than those observed with static stretching (SS) alone,\(^5\) FR does not appear to acutely diminish strength and power,\(^6\) unlike long bouts of SS (>60 s).\(^6\) Most FR studies have assessed the ROM of tissues comprised of both contractile and non-contractile elements.\(^7\) Indeed, assessments of quadriceps,\(^8\) hamstrings,\(^8\) plantar flexors,\(^9,10\) and other commonly-rolled muscle groups appear to indicate FR’s efficacy in acute ROM increases.\(^2\) However, another commonly-rolled portion of the thigh, the iliobial (IT) band, is not comprised of contractile tissue. It is a large, dense, fibrous portion of connective tissue located on the lateral aspect of the thigh.\(^11\) While the precise mechanisms underlying the ROM improvements associated with FR remain unclear,\(^12\) it is plausible that a largely fibrous tissue with less contractile elements will respond differently to treatment than one comprised largely of skeletal muscle. To the authors knowledge, only one study has explored FR applied to the non-contractile IT band, and no change in ROM was observed.\(^13\)

Stretching, pain relief techniques, and other conservative treatments typically serve as the first line of therapy for IT band-related pathologies,\(^11\) such as IT band syndrome (ITBS).\(^14\) Iliobial band syndrome is a common overuse injury often observed in runners and cyclists. Patients typically report lateral knee pain during repetitive lower-limb activities.\(^14\) Foam rolling has been shown to improve ROM\(^1\) and limited evidence suggests it may be effective for reducing sensations of pain.\(^4,15–18\) Though the efficacy for treating ITBS with FR has not been directly assessed, it is a common treatment in many rehabilitation settings.\(^19\) To date, the efficacy of FR as a therapeutic intervention for ITBS remains unclear. Patients with ITBS commonly demonstrate diminished hip adduction,\(^11\) possibly limited by the IT band’s lack of extensibility. Thus, a treatment that could potentially improve hip adduction and reduce sensations of pain may offer value.

Clinical interventions that attempt to elongate the IT band have been widely used in physical rehabilitation.\(^20\) However, the capacity of the IT band to undergo elongation as a result of therapeutic interventions is an ongoing area of debate.\(^20\) Elongation interventions targeting the IT band, including the use of FR, have been recommended largely on the basis of clinical experience, and on the observation and measurement of increased hip adduction ROM after an intervention.\(^20\)

Chaudhry et al.\(^20\) used a three-dimensional mathematical model for deformation of human fasciae in manual therapy to predict that a load of 9075N (925kg) and a tangential force of 4515N (460kg) would be required to produce even 1% compression and 1% shear. The authors noted that these predicted levels of forces are well beyond the physiologic range of manual therapy. Despite their findings, the authors speculated that mechanical stimulation of fascial mechanoreceptors may create changes in neural drive to skeletal muscle fibers connected to the IT band, which may explain the observed increases in hip adduction ROM seen in clinical practice following stretching, manual therapy, and FR.\(^20\) They further postulated that in vivo fascia may respond to mechanostimulation with an altered tonus regulation of its own.\(^20\)

Empirical data supporting or refuting clinical observations of hip adduction improvements following FR may assist the practitioner’s decision-making process. Additionally, an understanding of both the degree and duration of any change may be useful, as well. Despite acute ROM increases, limited evidence suggests a lack of chronic FR-induced improvements.\(^21\) Thus, at some point in time following FR, any improvements in ROM can be expected to dissipate. Previous investigations concerning contractile tissues have typically observed ROM increases lasting up to 10 minutes, with the effects fully dissipated at 30 minutes.\(^22\) The duration of ROM changes following FR of non-contractile tissues has not been examined. This information could potentially benefit patient care, especially if FR is combined with other interventions directed at increasing ROM. The purpose of this study was to examine the impact of FR the IT band on hip adduction ROM and the short-term time course of any ROM changes that may occur. The hypothesis was that following FR of the IT band, hip adduction would increase compared to a control condition and that these increases would dissipate within twenty minutes.

METHODS

SUBJECTS

Subjects included 34 healthy adults (21 female, 13 male) (female mean age: 24.67 ± 8.6 yrs, height 161.4 ± 9.8 cm, mass 67.5 ± 12.3 kg; male mean age 22 ± 2.5 yrs, height 170.2 ± 8.2 cm, mass 76.3 ± 21.9 kg). Subjects were eligible for inclusion in the study if the medial joint line of the knee failed to reach the table during an Ober’s test and if they had no lower extremity injury within the last six months. Prior to the first testing session, subjects provided informed consent as approved by the University Institutional Review Board. All procedures were approved by the University Institutional Review Board (IRB registration number: 00006274). Based upon previous research,\(^1,5,9,10,13\) approximately 10 to 30 subjects per condition in a within-subject experimental design were determined as sufficient to observe a significant difference in the primary outcome measure of ROM.

OBER’S TEST

Ober’s test is a clinical examination technique used to assess the extensibility of the IT band from its proximal origin at the tensor fascia lata to its distal insertion into the anterolateral tibia.\(^23,24\) The subject was positioned side-lying with the leg being tested on top, the bottom leg flexed for stability, and the hips stacked perpendicular to the table.
The subject was positioned at the edge of the table to ensure that the lower leg and foot do not limit ROM. Positioned behind the subject, the examiner stabilized the pelvis proximally to maintain the stacked position for the hip to ensure proper lumbar and pelvic position. The examiner supported the lower leg distally at the anterior knee in order to limit potential hip internal or external rotation. By maintaining the hip in a neutral position with the distal hand around the anterior knee, the examiner was able to appreciate the end feel for the point of restriction as the subject’s leg moves into adduction. The examiner passively brought the leg into abduction and extension before slowly releasing the lower limb toward the table with the knee flexed to approximately 10 degrees. The examiner identified the point of tissue restriction, which was indicated by restricted adduction of the thigh. In the present investigation, a second examiner was responsible for measuring the distance from the medial joint line to the top edge of the table in centimeters and provided additional visual observation to prevent any errors. The use of a tape measure to quantify the Ober’s Test has been described by Doucette and Goble.25

EXPERIMENTAL DESIGN

A counterbalanced, repeated measures design was used to assess how FR the IT band influences hip adduction ROM and how long any changes were retained. Each subject completed two sessions on separate days; one where FR occurred and one where a 5-minute walk was performed as a control treatment, followed by a series of Ober’s tests. Subjects were assigned to start with either the experimental or control condition in an alternating fashion to control for order effects. The dependent variable was hip adduction ROM as assessed by the Ober’s test, specifically measured in cm between the medial joint line of the knee to the top of the treatment table. The independent variable was the condition, either FR prior to Ober’s test measurements or not FR prior.

A baseline Ober’s test was performed upon entry to the laboratory on both testing days. Figure 1 displays Ober’s test, as it was performed in this investigation. Subjects then completed the FR protocol or the control treatment. When performing the FR protocol using a high-density foam roller (Thera-Band®, Performance Health, Warrenville, IL, USA), subjects were instructed to roll the lateral portion of each thigh, from the greater trochanter to the lateral epicondyle of the knee. During FR, subjects were instructed to maintain a position that kept the lateral aspect of the thigh in contact with the roller. A clinician, a licensed athletic trainer, observed the FR interventions and identified any substitutions and offered corrective feedback. The technique of FR from between the greater trochanter and the lateral epicondyle of the femur was employed to mimic typical clinical usage and guidelines. Subjects completed three 20-second FR bouts, each interspersed with a 20-second rest. Subjects were instructed to use a standardized FR technique by planting the foot and hands of the side opposite to that being rolled on the ground and shifting enough weight to those points so that pain did not exceed 6 on a scale of 10. A tempo of 3 seconds down and 3 seconds up the leg was maintained across FR bouts.

Figure 1: Ober’s test

Following the FR treatment or the 5-minute walk, the Ober’s test was repeated immediately (less than 1 minute), 3 minutes, 10 minutes, 15 minutes, and 20 minutes to assess changes in hip adduction ROM over time. The Ober’s test was performed by the same clinician across subjects. This clinician, a licensed physical therapist and athletic trainer, was blinded to the conditions and was solely responsible for conducting the Ober’s test. The second clinician, a licensed athletic trainer, performed the measurement and observed for errors. The intrarater reliability of the Ober’s test using a bubble inclinometer ranged from 0.91 and 0.94.26 Intrarater reliability using a tape measure has not yet been reported in the literature.

STATISTICAL ANALYSIS

A two-way analysis of variance (ANOVA) was used to compare results for condition (FR vs. CON) across time (baseline, immediately, 3 minutes, 10 minutes, and 20 minutes post). Bonferroni post-hoc tests were conducted to compare replicate means by row. Alpha level was set at $p = 0.05$. Cohen’s $d$ effect sizes were calculated for all significant differences observed to determine the magnitude of effect. An effect size equal to or in excess of 0.2, 0.5, and 0.8 were considered small, moderate, and large effects, respectively.27 All data analysis was completed using GraphPad Prism 5.0 (GraphPad Software San Diego, CA, USA).

RESULTS

Figure 2 displays changes in Ober test measurement over time following FR. Ober’s test ROM was significantly greater in FR compared to CON immediately post-treatment (24.2 cm ± 6.3 vs. 28.2 cm ± 6.3, $p = 0.00$, $d = 0.59$), with a moderate effect observed, and three minutes post (24.6 cm ± 7.6 vs. 28.3 cm ± 5.9, $p = 0.00$, $d = 0.56$), with a moderate effect observed. No differences were observed between groups at baseline (27.9 cm ± 7.5 vs. 27.7 cm ± 6.6, $p > 0.05$, $d = 0.28$) 10 minutes post (26.4 cm ± 5.4 vs. 27.8 cm ± 5.5, $p > 0.05$, $d = 0.26$), 15 minutes post (27.4 cm ± 6.3 vs. 27.4 cm ± 5.7, $p > 0.05$, $d = 0.05$), or 20 minutes post FR or CON (27.7 cm ± 6.4 vs.
DISCUSSION

The first objective of this study was to investigate the influence of FR the IT band on hip adduction ROM. The second objective of this study was to assess the short-term time course of any ROM changes observed following FR of the IT band. The first important finding in this study was that FR the IT Band for three bouts of 20 seconds increased hip adduction ROM as measured by the Ober’s test. The second important finding in this study was that the observed increases in hip adduction ROM following FR dissipated sometime between three minutes and 10 minutes post-treatment. These findings indicate that 5 bouts of 20 seconds of FR can transiently increase ROM, even in a region primarily composed of non-contractile tissue. Further, the short-lived changes may have implications for the way FR is performed in both therapeutic and performance-oriented settings.

While transient increases in ROM are typically observed following FR, the only other study assessing non-contractile tissue (also performed on the IT band) did not observe such a difference. Given the apparent similarities between that study and the present investigation, the reason for the contrasting findings is unclear. Hall and Smith instructed subjects to roll their IT band with an upright torso, while subjects in the present investigation positioned their torso parallel with the ground. While the former position may have decreased sensations of discomfort at the point of contact with the roller, Grabow et al. reported that higher rolling forces of the quadriceps did not amplify ROM increases. In the Hall and Smith study, subjects utilized a faster rolling cadence, transitioning up and down the length of the femur in two seconds, compared to the three seconds utilized in the present investigation. The influence of FR tempo on ROM has not been directly assessed, though it is plausible that slower tempos could result in greater increases. Another factor that may have influenced the differing outcomes of the present investigation and those of Hall and Smith could be the degree to which contractile tissues were influenced. In the present investigation, care was taken to focus on the non-contractile IT band to the greatest extent possible. Nevertheless, adjacent contractile tissues may have been influenced differently compared to the investigation by Hall and Smith, via altered exposure to the FR treatment. Subtle procedural differences between investigations will likely persist as a confounding variable in FR research, given the nature of the treatment.

To the authors' knowledge, the time course of changes in ROM following FR has only been investigated in conjunction with static stretching. While ROM was increased immediately post-treatment in that investigation, the effects had dissipated by 30 minutes. The quadriceps and hamstring muscles, two contractile muscle groups, were rolled in that investigation; therefore, similar outcomes might be expected in other contractile tissues. Based on the findings of the present investigation, increases in ROM may persist for at least three minutes after FR the IT band, with values returning to baseline some time before the 10-minute mark. While the increases in ROM observed in the present investigation reached statistical significance, they appear to be less pronounced than increases in trials assessing myofascial rolling treatment of contractile tissue. It stands to reason that while increases in ROM can potentially be attained by FR non-contractile tissues, the increases may be smaller and shorter-lived than those observed following treatment of contractile tissues.

The physiological underpinnings of ROM changes following FR are unclear, regardless of tissue type. There exists little consensus as to what specifically is modulated during treatment. Both local and global explanations have been put forth. Using acoustic radiation force imaging, Heiss et al. reported a 15% decrease in tissue stiffness of the IT band following FR. Despite the typically immediate and short-lived effects of FR, this decrease in stiffness was not apparent until 30 minutes after FR. Hotfiel et al. reported an increase in peak blood flow following FR of the lateral thigh, with increases of 73.6% immediately following FR and 52.7% at 30 minutes following FR. It is plausible that some combination of reductions in tissue stiffness and increases in local blood flow could explain the increased ROM observed following FR. In regards to potential non-local mechanisms, Behm and Wilke suggested that FR may activate global modulatory pain systems. This could potentially increase an individual’s degree of stretch tolerance to that which may have been prohibitively uncomfortable prior to treatment. Non-local effects have indeed been evident in a number of investigations. In some instances, joints contralateral to the one undergoing FR have increased ROM. Other findings include increased hamstring flexibility after FR of the plantar fascia, and hamstring FR influencing ROM in a region as remote as the shoulders. Additionally, Young et al. reported decreased Hoffman reflex responses after roller massage. These non-local effects would seem to confirm at least some degree of neural influence of FR.

In light of the non-local effects of FR, a favorable response to treatment for the IT band appears more plausible. Under a framework in which dense, rigid tissues needed to be mechanically altered for ROM to increase, successfully modifying the tension of the IT band with 60 cumulative seconds of FR would seem improbable. But considering
the growing body of evidence that influential factors likely go beyond the mechanical, the findings of the present investigation are less surprising. While the approximate 3 to 10 minute time window of increased ROM may be limited to the IT band, the precise timeframe one can expect to maintain their increased ROM following FR warrants further exploration. The desired outcome of a FR session may dictate the importance of precise timing as well. If performed to expedite muscle recovery between training sessions or competitions, timing may be less critical. If FR is performed pre-training or pre-competition, timing may be immensely critical. For example, prior to a race, a hurdler may foam roll to increase ROM, eschewing static stretching for fear of decreasing muscular power and compromising sprinting speed. It is plausible that if FR is performed too long prior to competition, they will not reap the benefits. Similarly, in a therapeutic setting, a practitioner utilizing FR for a patient may stand to benefit knowing exactly how long they can expect any increases in ROM to persist. With that information, they may be able to functionally utilize that increased ROM within a therapy session.

This study had several limitations. First, the findings are limited to the rolling duration used. The influence of FR on hip abduction may be different if other lengths of treatment are used. Second, the IT band was the only area rolled. The influence of FR on ROM appears to vary considerably based on the specific area treated. Third, it is possible that nearby tissues such as the tensor fascia lata, vastus lateralis, and biceps femoris were influenced by the FR protocol. Changes in those tissues may have impacted the results. Fourth, it is possible that the observed improvements in hip abduction ROM were not specifically due to FR, the IT band, or any specific tissue, but a global neurophysiological response that happened to be evident at the joint assessed. Foam rolling other areas with less obvious pertinence to hip abduction may result in similar outcomes. Fifth, given the intervals where data was collected, it cannot be determined where ROM was no longer increased after the three-minute mark. Sixth, intrarater reliability was not assessed for the clinicians performing and measured the Ober’s Test using the tape measure methodology. Finally, subjects were not blinded in this study. The inability to blind subjects will likely remain a limitation in all FR investigations.

CONCLUSIONS

The findings of the present investigation support the hypothesis that FR applied to the IT band increases hip abduction ROM as measured by the Ober’s test immediately post-treatment and at three minutes post-treatment. Foam rolling may be a useful tool for temporarily increasing hip abduction ROM. Practitioners should be aware that these changes are short-lived, and that a treatment intended to work in conjunction with increased hip abduction should transpire in a time-sensitive manner.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts to report.

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Original Research

Sex and Age Comparisons in Neuromuscular And Biomechanical Characteristics of the Knee in Young Athletes

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Background
The identification of risk factors for injury is a key step for musculoskeletal injury prevention in youth sports. Not identifying and correcting for injury risk factors may result in lost opportunity for athletic development. Physical maturation and sex affect these characteristics, which may indicate the need for both age and sex-based injury prevention programs.

Hypothesis/Purpose
This study examined age and sex differences in knee strength, static balance, jump height, and lower extremity landing biomechanics in school- and high school-age athletes.

Study Design
Cross-sectional

Methods
Forty healthy school aged (10.8±0.8 yrs) and forty high school (16.8±0.8 yrs) athletes completed isokinetic knee flexion and extension strength tests, single-leg static balance and single-leg vertical stop jump tasks.

Results
High school athletes were significantly stronger (~67% and 35% stronger for males and females, respectively) and jumped higher (regardless of sex) compared to school age athletes. High school males had worse balance (~28%) compared to their younger counterparts. High school females had lower strength (~23%) compared to males but had better balance (~46%). Conclusion: Maturation had different effects on the variables analyzed and sex differences were mainly observed after maturation. These differences may be minimized through appropriate age and sex specific training programs.

Levels of Evidence
3a

Clinical Relevance
Neuromuscular and biomechanical differences between sex and age groups should be accounted for in injury prevention and rehabilitation. Inadequate training may be a primary factor contributing to injuries in a young athletic population. When designing training programs for long term athlete development, programs should be dependent on decrements seen at specific time points throughout maturation. What is known about the subject: Generally, both males and females get stronger and jump higher as they get older but the results comparing balance and biomechanics...
between genders or across age groups have been mixed. What this study adds to existing knowledge: The current study looks at multiple neuromuscular and biomechanical variables in male and female participants at different maturation statuses. The current data supports the significant changes observed in strength and jump height, as both genders age, but the data also demonstrates significant differences in balance between age groups in males and between genders in balance and knee flexion angles.

INTRODUCTION

There are an estimated 30 to 45 million youth, ages 6 to 18 years, participating in athletics in the United States and approximately one third of these youth athletes seek attention for sport related injuries. The number of injuries in adolescents has been on the rise, causing concern for long term problems with compromised quality of life and increased risk of further injury. Injuries to the anterior cruciate ligament (ACL) often occur between 16-18 years of age, however, the frequency of injury between the ages of 11-12 years has been steadily increasing. Sex differences in injury rates have been reported across a wide range of sports, indicating a need for intervention at a young age. At the high school setting, ACL injury rates for females have been shown to be higher than males (IRR 2.30), with the largest difference in basketball athletes (IRR 3.68). A higher female ACL injury rate was also seen at the collegiate level, with females higher than males (IRR 2.49), and the greatest difference being between baseball and softball athletes (ITT 6.61).

Previous literature has demonstrated decreased neuromuscular control in females compared to males. Multiple factors may predispose adolescents to injury, before including extrinsic mechanisms of injury in sport. Risk factors for injury in youth include lack of muscular strength, balance, decreased knee flexion moment, and increased knee valgus moment. To counteract these risk factors, the optimal age to introduce specific training interventions has been debated. During adolescence, males and females experience skeletal, neuroendocrine and sexual maturation developments that make injury prevention strategies and training prescription a complex process. There has been limited success of athlete development programs; as athlete development should be based on individually unique and constantly changing characteristics, including the demands of normal physical growth, biological maturation, behavioral development and their interactions. Challenges in factors associated with maturation and sex must be considered when creating guidelines to develop healthy, resilient young athletes.

Athletic development is multidimensional and difficult to assess in youth, as trajectories from novice to elite can vary greatly among athletes. The mechanism for sex differences in lower extremity injury rates remains unknown despite a multitude of kinematic and kinetic studies. It is essential to identify sex related physical and physiological differences that occur because of maturation, as these may help identify risk factors that lead to injury rate differences between sexes.

Factors underlying sex differences in injury rate have previously been categorized into several general theories: anatomical, hormonal and biomechanical. Previous literature has individually examined maturation’s effect on gender differences in strength, static balance, knee kinematics, and vertical jump. However, previous research has not examined multiple risk factors together in one participant population. Understanding associations in injury risk factors and injury patterns play an important role in the development of injury prevention strategies.

The purpose of this study was to examine and compare strength, static balance, jump height, and landing kinematics characteristics in school age and high school athletes based on sex and age. It was hypothesized that (1) as age increases, strength and performance of both sexes will improve; furthermore, (2) knee joint flexion angles measured at initial contact and peak flexion will decrease at the high school level. Additionally, (3) males will perform better on strength, biomechanics, and performance than females at the high school level, while (4) females will perform better with balance. Recognizing neuromuscular and biomechanical differences between sexes at different ages will help better develop healthy, resilient youth athletes.

METHODS

PARTICIPANTS

Forty healthy school aged (10.8±0.8 yrs) and forty high school (16.8±0.8 yrs) athletes with a similar distribution of males and females within each group participated in the study. Self-assessed Tanner Scale stage was used to ensure participants fell into one of two categories: prepubertal (stage 1) for school aged athletes or post pubertal (stage 4 of 4) for high school aged. All participants participated in organized sports that required jumping, cutting and landing, at least three times per week. Injury prevention programs have been shown to induce favorable neuromuscular and biomechanical changes, therefore all athletes in this study did not participate in any form of injury prevention training at any time before or during data collection. Participants were excluded if they had any self-reported history of serious lower extremity musculoskeletal injury (such as ligament rupture), musculoskeletal injury within the last six months or any history of rheumatological disorder, cerebral vascular accident, peripheral nerve disorder, or any other disorder that interferes with sensory input and/or motor function. All participants were informed of testing procedures and provided written consent (or assent as appropriate) that was approved by the University’s Institutional Review Board. All testing was conducted at the Neuromuscular Research Laboratory within the University. Reliability of testing procedures has been established previously.

INSTRUMENTATION

Isokinetic strength was collected for the knee flexors and
extensors utilizing the Biodex System 3 Multi-Joint testing and Rehabilitation System (Biodex Medical Inc., Shirley, NY). Ground reaction forces during static balance testing and the single-leg stop-jump task were collected utilizing two force plates (Kistler Corporation, Worthington, OH; Model #4060-1011000). Ground reaction force data was collected at 1200 Hz during the single-leg stop-jump task and at 100 Hz during the balance testing. Three-dimensional coordinate data from 15 retroreflective markers during the single-leg stop-jump task were collected and calculated using a 3D optical capture system (Peak Performance Technologies, Inc., Englewood, CO). This motion analysis system includes six high speed (120 Hz) optical cameras (Pulnix Industrial Product Division, Sunnyvale, CA) instrumented and synchronized using Peak Motus software (version 7.2, Peak Performance Technologies, Inc., Englewood, CO).

PROCEDURES

All participants completed balance assessments first, followed by strength then single-leg vertical stop jump task. Lower extremity segment lengths and joint widths of each participant were taken of the lower extremity in addition to body mass (kilograms) and standing height (meters). The Biodex System was used to test dominant leg muscle strength of the quadriceps and hamstrings musculature during an isokinetic knee flexion and extension test. Leg dominance was defined as the leg a participant would naturally use to kick a soccer ball. Participants were secured in the chair with straps to isolate the tested movement, range of motion was set to allow for zero to 90 degrees of rotation (based on the attachment arm); and provided a warm-up session of three repetitions at 50% of maximum effort and three repetitions at 100% of maximum effort. Participants were instructed to give maximum effort throughout the entire test. Five maximal quadriceps and hamstring contractions at 60º/sec were performed with one minute of rest between all sessions.

Single-leg balance testing was performed bilaterally for each participant with eyes open and closed. Five trials (ten seconds each) for each condition per leg were collected. Order of testing (by condition) was determined by simple randomization prior to data collection and participants were given one practice trial for each condition and for each leg prior to testing. The testing position was unilateral stance with the untested leg flexed slightly at the hip and the knee with hands on hips. Participants were instructed to remain "as still as possible" throughout each trial and to regain the test position as quickly as possible if there is a loss of balance. Touchdowns on the force plate were acceptable, as they added to the variability in balance measurement. Trials were excluded if the participant touched down off the force plate because it would not be contributing to the force-platform measure.

Fifteen retroreflective markers were utilized for data collection of 3D coordinate data during the single-leg vertical stop-jump task. During the single-leg vertical stop jump task, retroreflective markers were placed bilaterally over the second metatarsal head, posterior aspect of the heel, lateral malleolus, femoral epicondyle, anterior superior iliac spine, and the L5-S1 disc space. Four other markers were attached to wands (approximate length 0.07 m) and secured bilaterally with Velcro straps and athletic tape to the lateral aspect of the participant’s thigh and shank.

The single-leg vertical stop jump task consisted of the following: 1) initial starting point measured as 40% of the participant’s height from the edge of the force plates, 2) jump with a single-leg landing on a force plate, 3) immediate jump for maximum vertical height following landing on the force plate, and 4) landing in approximately the same location from which the maximal jump was initiated (Figure 1). Participants were given a verbal description, visual demonstration, and five practice trials on each leg in order to assure familiarity with the task. The first five good trials were used for data processing. A good trial was defined as a trial during which the participant performed the task with the proper technique, landed successfully on the force plate and did not touch down outside the force plate.

DATA REDUCTION

The Biodex Advantage Software v3.0 was used to calculate the absolute peak torque and average peak torque normalized to body weight (%BW) (mass x gravity) for the isokinetic strength test of the quadriceps and hamstrings for each leg. Additionally, the hamstring:quadriceps ratio was calculated for absolute peak torque and peak torque normalized to body weight. Single leg balance ground reaction force data were processed through a custom Matlab (MathWorks, Natick, MA) script. Ground reaction force data were passed through a zero-lag 4th order low pass Butterworth filter with a 100 Hz cutoff frequency. The standard deviation (SD) for each component ground reaction force (anterior-posterior, medial-lateral and vertical ground reaction force) was calculated during the entire trial and then averaged across all five static balance trials. Lower extremity kinematic and kinetic data of the single-leg vertical stop jump was calculated using Kinecalc module of the Peak Motus software package (Peak Performance Technologies, Inc., Englewood, CO). Vertical jump height was measured as the difference between the sacral marker during the static trial and the maximum during jump trial, and then calculated as percent body height (%BH). Kinematic data were calculated as previously published on reactive tasks. Raw analog data from the force plates were used to calculate the ground reaction force data for each vertical stop jump trial. The ground reaction force data were used to calculate the
peak vertical ground reaction force during the initial stance phase of the single-leg stop-jump task. This point was then identified in the joint kinematic data to determine knee flexion/extension and the knee valgus/varus angle at initial contact. Vertical stop jump peak vertical ground reaction force data were then normalized to percent body weight. Data were averaged across five trials.

STATISTICAL METHODS

All statistical analysis was performed using SPSS version 21.0 (SPSS Inc., Chicago, IL). Analyses consisted of: descriptive statistics (mean, standard deviation) for each age group and sex were calculated; independent t-tests for comparison of demographic data; two-way analysis of variance (ANOVA) to examine the effect of age group and sex on each variable; and multiple pairwise comparisons at the level of the interaction to assess differences between age group and sex. Additionally, Cohen’s $d$ effect size was calculated to assess the magnitude of difference between each pairwise comparison.

RESULTS

There were significant differences between sexes for high school athletes in height ($p<0.001$) and weight ($p<0.001$) (Table 1), with males being taller and heavier.

At the high school age, males were shown to be stronger than females in knee flexion and extension strength, both for average peak torque ($p<0.001$) and relative to body weight ($p<0.001$). (Table 2) High school aged athletes, compared to school age athletes, were stronger in knee flexion and extension strength, both for average peak torque ($p<0.001$) and relative to body weight ($p<0.001$). High school aged athletes had a larger hamstring:quadriceps ratio relative to body weight (males $p=0.031$, females $p=0.046$). Female high school aged athletes had a larger absolute peak torque hamstring:quadriceps ratio ($p=0.041$) (Table 2).

School aged females demonstrated significantly better static balance than school aged males in the anterior-posterior (AP) ($p=0.047$) and the medial-lateral (ML) ($p=0.018$) directions with eyes opened and ML direction with eyes closed ($p=0.027$). High school aged females demonstrated better static balance than high school aged males, in all directions, with eyes opened and closed. (Table 3) Males exhibited better static balance at the school age, compared to high school, in the AP and ML directions with both eyes opened ($p=0.001$, $p<0.001$, respectively) and eyes closed ($p=0.001$, $p=0.001$). Whereas females only displayed better static balance at the school age in the ML direction with eyes closed ($p=0.050$). (Table 3)

Within the single-leg stop-jump task, males at the school age displayed greater peak knee flexion angle ($p=0.011$) than females. At the high school age, males demonstrated greater peak knee flexion angle ($p=0.011$) and jump height ($p<0.001$) than females. (Table 4) Both males and females performed greater jump heights at the high school age compared to school age ($p<0.001$) and males showed greater vertical ground reaction forces at the high school age ($p=0.034$). (Table 4)
Table 2: Effects of age and sex on average isokinetic knee strength

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<td>34.75 ± 12.76</td>
<td>103.26 ± 21.65</td>
<td>31.42 ± 36.98</td>
<td>69.84 ± 23.66</td>
<td>&lt;0.001</td>
<td>0.230</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Knee extension average peak torque (Nm)</td>
<td>73.20 ± 21.65</td>
<td>201.66 ± 36.98</td>
<td>66.19 ± 23.66</td>
<td>137.35 ± 26.79</td>
<td>&lt;0.001</td>
<td>0.106</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Average peak torque hamstring:quadriceps ratio</td>
<td>0.47 ± 0.11</td>
<td>0.52 ± 0.12</td>
<td>0.47 ± 0.10</td>
<td>0.52 ± 0.10</td>
<td>0.894</td>
<td>0.878</td>
<td>0.736</td>
<td>0.057</td>
</tr>
<tr>
<td>Knee flexion average peak torque (%BW)</td>
<td>87.09 ± 18.00</td>
<td>152.30 ± 22.03</td>
<td>87.07 ± 23.12</td>
<td>122.71 ± 18.95</td>
<td>&lt;0.001</td>
<td>0.762</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Knee extension average peak torque (%BW)</td>
<td>182.90 ± 29.86</td>
<td>291.44 ± 44.27</td>
<td>184.26 ± 36.28</td>
<td>238.06 ± 27.50</td>
<td>&lt;0.001</td>
<td>0.714</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>%BW hamstring:quadriceps ratio</td>
<td>0.48 ± 0.10</td>
<td>0.53 ± 0.11</td>
<td>0.47 ± 0.10</td>
<td>0.52 ± 0.09</td>
<td>0.851</td>
<td>0.773</td>
<td>0.581</td>
<td>0.031</td>
</tr>
</tbody>
</table>

All measurements at 60%. Mean ± sd.  
BW= body weight  
Significance set at 0.05 level
Table 3: Effects of age and sex on static balance ground reaction force standard deviation in eyes open and closed conditions

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>School High School School High School</td>
<td>Interaction</td>
<td>School High School Males Females</td>
</tr>
<tr>
<td>Eyes open - AP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.16 ± 1.12</td>
<td>2.67 ± 0.84</td>
<td>1.72 ± 0.80</td>
<td>1.81 ± 0.48</td>
</tr>
<tr>
<td>Eyes open - ML</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.71 ± 1.57</td>
<td>3.61 ± 1.57</td>
<td>2.12 ± 1.20</td>
<td>2.28 ± 0.77</td>
</tr>
<tr>
<td>Eyes open - V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.53 ± 3.08</td>
<td>4.65 ± 1.89</td>
<td>3.75 ± 2.55</td>
<td>2.98 ± 1.11</td>
</tr>
<tr>
<td>Eyes closed - AP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.43 ± 2.40</td>
<td>5.49 ± 1.65</td>
<td>3.71 ± 2.11</td>
<td>3.87 ± 1.11</td>
</tr>
<tr>
<td>Eyes closed - ML</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.72 ± 3.39</td>
<td>8.87 ± 3.22</td>
<td>5.35 ± 3.10</td>
<td>6.29 ± 2.81</td>
</tr>
<tr>
<td>Eyes closed - V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.94 ± 7.59</td>
<td>11.40 ± 4.42</td>
<td>9.61 ± 6.44</td>
<td>8.63 ± 5.50</td>
</tr>
</tbody>
</table>

**Pairwise Comparison**

Mean ± sd

**AP = anterior-posterior, ML = medial-lateral, V = vertical**

Table 4: Effects of age and sex on single leg stop jump knee joint angles, jump height and vertical ground reaction force

<table>
<thead>
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<th>ANOVA</th>
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</thead>
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<td></td>
<td>School High School School High School</td>
<td>Interaction</td>
<td>School High School Males Females</td>
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<tr>
<td>knee flex @ IC (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.55 ± 7.41</td>
<td>11.96 ± 5.39</td>
<td>13.89 ± 7.09</td>
<td>12.54 ± 6.62</td>
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<tr>
<td>knee AB/AD @ IC (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.83 ± 8.07</td>
<td>1.41 ± 5.37</td>
<td>2.48 ± 7.78</td>
<td>2.95 ± 4.41</td>
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<tr>
<td>peak knee flex (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43.30 ± 11.54</td>
<td>45.61 ± 11.53</td>
<td>37.39 ± 10.68</td>
<td>41.41 ± 9.27</td>
</tr>
<tr>
<td>jump height (%BH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.38 ± 3.98</td>
<td>21.24 ± 3.05</td>
<td>12.78 ± 3.50</td>
<td>16.19 ± 2.82</td>
</tr>
<tr>
<td>peak vGRF (%BW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.48 ± 0.72</td>
<td>3.76 ± 0.65</td>
<td>3.63 ± 0.76</td>
<td>3.39 ± 0.54</td>
</tr>
</tbody>
</table>

**Pairwise Comparison**

Mean ± sd

**IC = initial contact, vGRF = vertical ground reaction force.**

DISCUSSION

Children and adolescents are subjected to a maturation process that is not linear, creating the need for periodic assessment to correctly define and change training programs. This study examined the effects of sex and age on modifiable musculoskeletal and neuromuscular characteristics to help inform effective training programs. Unlike previous literature, the current study looked...
at multiple variables in the same participant. The results observed in this study predominantly supported the hypotheses. Differences after maturation were seen in strength, balance, and biomechanics. These findings showed increased in strength and jump performance in both sexes and decreases in male static balance as age increased. We saw limited differences between sexes at the school age. In this study, both sexes had a significant increase in height and weight through maturation, although high school aged male athletes were on average almost 15kg heavier than their female counterpart (Table 1). With one-third of youth requiring medical attention for activity-related injuries, it is essential to understand the effect of growth, development and sex-related physiological differences on sports injury and performance. Development of muscular strength, balance and proper mechanics through age and sex appropriate interventions is essential for sustainable long-term athletic performance. Identifying neuromuscular differences between sexes and changes throughout maturation can help to develop specific training techniques to reduce the incidence of these injuries.

**ISOKINETIC KNEE STRENGTH**

Dynamic knee stability is essential in an athlete’s safety while participating in activities that require cutting, jumping, and landing. Co-contraction of the hamstrings and quadriceps muscles has been found to stabilize the knee and an imbalance in hamstrings to quadriceps strength may be of significance in non-contact leg injuries. The current study shows a significant increase in the ratio of hamstring-to-quadriceps strength, normalized to body weight, from the school to high school age of male and female athletes but no difference between sex. This demonstrates that while the hamstrings and quadriceps of both sexes increased with age, hamstring strength increased to a greater extent. Previous work that found significant differences in hamstring-to-quadriceps strength ratio between sex in 9-12 year old. This may be due to their participants being children recruited from local schools rather than specifically using athletes as in the current study. In young soccer athletes, an significant increase in hamstring-to-quadriceps strength ratio was seen from immature to mature females but not in males.

Moreover, knee stability is related to quadriceps and hamstring individual action at the knee; with quadriceps strength playing a vital role during landing to decelerate the body and absorb impact forces and the hamstrings controlling anterior tibial translation. It has been proposed that differences in muscular strength and sex specific neuromuscular activation patterns are one reason females have a greater risk of noncontact ACL injury. The current findings agree with previous research, that absolute and body weight corrected strength gains occur in both sexes after puberty and significant differences can be seen between sexes at the high school age (Table 2). Parallel to the current findings, the Physical Activity Guidelines released from the federal government reported that both sexes significantly increase strength through maturation. Their data show adolescent boys and girls exerted significantly more pounds of force with knee extension than younger boys and girls. Similarly, significant increases in quadriceps and hamstring strength were seen with maturity in male and female soccer players. Barber-Westin et al. also found significant strength differences as chronological age increases. Thirteen-year-old female athletes were shown to have 20% greater knee extension peak torque than 9-year old, while 14-year-old male athletes had 38% greater peak torque than 9-year old. It was also found that no significant differences in knee extension or flexion peak torque exist between sexes until the age of 14 years. Male athletes between 14-17 years had significantly greater extension and flexion peak torque than their female counterparts. Data also aligns with current findings that no significant difference in strength were seen between younger girls and boys (age 6-11) for knee extension but they did find significant differences between adolescent girls and boys (age 12-15). Decrement in muscular strength have been associated with the lack of dynamic stability surrounding lower extremity joints, potentially resulting decreased balance ability.

**STATIC BALANCE GROUND REACTION FORCE**

Poor balance has been significantly associated with an increased risk of lower extremity injury. One measure is single leg static balance, requiring an athlete to minimize center of mass movement over a small base of support, is related to the unconscious neuromuscular control and stabilization of joints. Balance begins to emerge as a trainable motor skill from the age of 10, therefore this study evaluated static balance as a prerequisite to the additional coordination needed for dynamic balance. This study showed significant decreases in static balance in male athletes as they reached the high school age (Table 3). This may be due to the greater physical growth that occurs in males during puberty. Increases in body weight have been shown to cause a decrease in balance, due to changes in center of mass. During puberty, growth changes may happen at a faster rate than the visual, vestibular and somatosensory systems can adapt. Increases in body weight, without increase in neuromuscular control, may be the cause of the disturbances in equilibrium seen in high school aged males. To decrease risk of injury in male athletes during and after puberty, prophylactic balance training may lead to task-specific neural adaptations. Additionally, training to improve balance can decrease risk of injury by enhancing agonist-antagonist muscle co-contractions which increases joint stiffness, and stabilizing joints against perturbations. Similar to knee stability, balance requires swift and constant feedback from visual, vestibular and somatosensory systems for coordinated movement to maintain balance. This study shows that female athletes have significantly better medial-lateral stability at both age groups (Table 3). All static balance measures were also significantly different between sexes in the high school age group. These results may be due to a lower center of gravity in females compared to males. While not assessed in this study, if females had smaller and lighter upper body with larger and heavier lower body, compared to males, this would increase the stability of their center of gravity. A difference in static balance at the high school age compared to females and to males at the school age may also be the result of increased...
strength seen in this study. However, Granacher and Golllhofer reported no significant associations between postural control and muscular strength. These current findings are consistent with previous literature that also revealed young females had significantly better static balance than males. Since balance and coordination are not fully matured in children, balance training is an important preparatory phase of athlete development for enhancing strength and power and reducing the risk of athletic injury.

SINGLE LEG STOP-JUMP

The vertical jump has been found to be a predictor of performance, running speed and agility. The neuromuscular spurt seen in adolescent boys throughout maturation causes increased power, strength and coordination. This growth spurt may explain why vertical jump height, a measure of whole body power, increases in boys during puberty but not usually in girls. Significant pubertal stage by sex interaction has been previously seen in maximum vertical jump height, with boys increasing jump height after puberty but not girls. However, the current study found a significant difference in both male and female athletes’ jump height through maturation (Table 4). Increased jump height at the high school age may be related to the increase in muscular strength seen in both sexes at the high school age. Differences in jump height between sex at the high school age may be due to increased testosterone levels in males. Following puberty, males have 15 times higher circulating testosterone concentration than in females. The biological effects of elevated testosterone include larger muscle mass and stiffer connective tissue, allowing males to exert greater muscular force more rapidly. However, this study did not assess hormone or associated hemoglobin levels in participants. This study only showed significant differences in peak vertical ground reaction forces (GRF) between school-aged and high school aged male athletes. Increased vertical GRFs in males at the high school age may be due to the larger increase in vertical jump height. Although jump height significantly increased at the high school age for both sexes, on average, males jumped 8 inches higher than their school age counterparts, while females only jumped 4 inches higher. No difference in vertical GRF was found between sexes at the school or high school age (Table 4). This differs from Pappas et al. who found females to have greater vertical GRF during jump tests than is found in male athletes. However, current results are similar to previous research that found no vertical GRF difference between sexes, but did report differences in rate of loading in which females reached vertical GRF 20% faster than males. It was proposed that decreased knee flexion and neuromuscular response reduces the ability of females to attenuate forces when landing. Lack of differences between sexes at each age group may be related to the speed in which participants decelerated, which was not assessed in the current study. These findings of no differences between sexes in knee kinematics at initial contact may also be associated with similar GRF values for both sexes.

Single-leg landings occur frequently in physical activity and sports. Proper biomechanics during landing can affect ground reaction force and loading of lower extremity structures, in turn preventing lower limbs injuries. This study showed no significant difference for either sex through maturation for knee flexion and abduction/adduction angles at initial or peak knee flexion angle during a single leg vertical stop jump task (Table 4). This is partially similar to Yu et al. who found no difference between ages for knee flexion angle at initial contact or peak flexion angle in male soccer players during a stop-jump task. However, they did find significant decrease in both knee flexion angles for female soccer players as they aged.

Initiating neuromuscular training in females at a younger age may help develop optimal movement strategies and mitigate the effects of puberty on dynamic control. As knee flexion angle increases, tensile stress on the ACL due to quadriceps muscle contraction has been shown to decrease. Neuromuscular training to develop hamstring and quadriceps co-contraction may protect the lower extremity during sport related movements. Significantly smaller peak knee flexion angles in females show the need for safe landing strategies, increasing knee flexion angle, at all ages. This may be related to muscle loading, which was not assessed in the current study. Decker et al. reported greater knee extensor and ankle plantarflexor energy absorption in females during drop jumps. This led to a more upright posture to maximize energy absorption at the hip and ankles. The current study did not find significant sex differences in knee flexion and abduction/adduction angle at initial contact in both the school aged and high school aged groups. Again, these results are similar to Yu et al. who also found that female youth soccer players had decreased knee flexion angles during a stop-jump task. Yet these results are different from previous findings that show knee valgus angle during landing to be greater in female athletes as compared to males. Increase in female knee valgus angles found in their study may be associated with the increase in female vertical GRF also seen in their study, neither of which were observed in the current study.

The current study had limitations, including the small sample size for each sex in the school aged and high school groups. Tanner staging by a trained health care professional has long been the medical standard. Therefore this study only included participants who self-assessed within stage 1 or stage 4 to reduce the chance of misclassification. Additionally, athletes in this study did not participate in the same sport, but all athletes did participate in sports that require jumping, cutting and landing (ie: soccer or basketball) to represent the types of sports in which non-contact ACL injury can occur. Activity frequency was a component of inclusion criteria to ensure athletes had similar general sport training. Neuromuscular training has been shown to alter strength and biomechanics in adolescent girls. Continued analysis of this data set can look for associations between variables measured, to determine what the potential cause of age and sex related differences may be. Future research examining an age and sex specific training intervention would be beneficial in minimizing significant changes in balance and biomechanics from the school to high school age.
CONCLUSION

There are a number of factors unique to the adolescent athlete during the period of growth and maturation that have the potential to increase injury risk. Examination of neuromuscular and biomechanical sex differences throughout growth and maturation may help identify risk factors that lead to injury rate differences. By assessing multiple factors within an individual participant, the current study gives a more comprehensive assessment of the athlete. This study showed significant increase in strength from school age to high school age in both sexes and that male athletes were significantly stronger at the high school age. Static balance was significantly better in male athletes at school age compared to high school aged. At the high school age, female athletes demonstrated significantly better static balance. Vertical stop jump height increased from the school age to the high school age in both sexes and peak knee flexion angles were greater in male athletes at both the school and high ages. Fitness and skill development occur on a constantly changing base of physical growth and biological maturation; these processes occur simultaneously and interact with each other and the demands of sport. It is important to understand how the role of sex and maturation influence athletic development for the most effective injury prevention and performance programs.

CONFLICTS OF INTEREST

The authors report no conflicts of interest related to this manuscript.

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REFERENCES


International Journal of Sports Physical Therapy


Background
The identification of risk factors for injury is a key step for musculoskeletal injury prevention in youth sports. Not identifying and correcting for injury risk factors may result in lost opportunity for athletic development. Physical maturation and sex affect these characteristics, which may indicate the need for both age and sex-based injury prevention programs.

Hypothesis/Purpose
This study examined age and sex differences in knee strength, static balance, jump height, and lower extremity landing biomechanics in school- and high school-age athletes.

Study Design
Cross-sectional

Methods
Forty healthy school aged (10.8±0.8 yrs) and forty high school (16.8±0.8 yrs) athletes completed isokinetic knee flexion and extension strength tests, single-leg static balance and single-leg vertical stop jump tasks.

Results
High school athletes were significantly stronger (~67% and 35% stronger for males and females, respectively) and jumped higher (regardless of sex) compared to school age athletes. High school males had worse balance (~28%) compared to their younger counterparts. High school females had lower strength (~23%) compared to males but had better balance (~46%). Conclusion: Maturation had different effects on the variables analyzed and sex differences were mainly observed after maturation. These differences may be minimized through appropriate age and sex specific training programs.

Levels of Evidence
3a

Clinical Relevance
Neuromuscular and biomechanical differences between sex and age groups should be accounted for in injury prevention and rehabilitation. Inadequate training may be a primary factor contributing to injuries in a young athletic population. When designing training programs for long term athlete development, programs should be dependent on decrements seen at specific time points throughout maturation.

What is known about the subject: Generally, both males and females get stronger and jump higher as they get older but the results comparing balance and biomechanics
INTRODUCTION

There are an estimated 30 to 45 million youth, ages 6 to 18 years, participating in athletics in the United States and approximately one third of these youth athletes seek attention for sport related injuries. The number of injuries in adolescents has been on the rise, causing concern for long term problems with compromised quality of life and increased risk of further injury. However, the frequency of injury between the ages of 11-12 years has been steadily increasing. Sex differences in injury rates have been reported across a wide range of sports, indicating a need for intervention at a young age. At the high school setting, ACL injury rates for females have been shown to be higher than males (IRR 2.30), with the largest difference in basketball athletes (IRR 3.68). A higher female ACL injury rate was also seen at the collegiate level, with females higher than males (IRR 2.49), and the greatest difference being between baseball and softball athletes (ITT 6.61).

Previous literature has demonstrated decreased neuromuscular control in females compared to males. Multiple factors may predispose adolescents to injury, before including extrinsic mechanisms of injury in sport. Risk factors for injury in youth include lack of muscular strength, balance, decreased knee flexion moment, and increased knee valgus moment. To counteract these risk factors, the optimal age to introduce specific training interventions has been debated. During adolescence, males and females experience skeletal, neuroendocrine and sexual maturation developments that make injury prevention strategies and training prescription a complex process. There has been limited success of athlete development programs; as athlete development should be based on individually unique and constantly changing characteristics, including the demands of normal physical growth, biological maturation, behavioral development and their interactions. Challenges in factors associated with maturation and sex must be considered when creating guidelines to develop healthy, resilient young athletes.

Athletic development is multidimensional and difficult to assess in youth, as trajectories from novice to elite can vary greatly among athletes. The mechanism for sex differences in lower extremity injury rates remains unknown despite a multitude of kinematic and kinetic studies. It is essential to identify sex related physical and physiological differences that occur because of maturation, as these may help identify risk factors that lead to injury rate differences between sexes.

Factors underlying sex differences in injury rate have previously been categorized into several general theories: anatomical, hormonal and biomechanical. Previous literature has individually examined maturation’s effect on gender differences in strength, static balance, knee kinematics, and vertical jump. However, previous research has not examined multiple risk factors together in one participant population. Understanding associations in injury risk factors and injury patterns play an important role in the development of injury prevention strategies.

The purpose of this study was to examine and compare strength, static balance, jump height, and landing kinematics characteristics in school age and high school athletes based on sex and age. It was hypothesized that (1) as age increases, strength and performance of both sexes will improve; furthermore, (2) knee joint flexion angles measured at initial contact and peak flexion will decrease at the high school level. Additionally, (3) males will perform better on strength, biomechanics, and performance than females at the high school level, while (4) females will perform better with balance. Recognizing neuromuscular and biomechanical differences between sexes at different ages will help better develop healthy, resilient youth athletes.

METHODS

PARTICIPANTS

Forty healthy school aged (10.8±0.8 yrs) and forty high school (16.8±0.8 yrs) athletes with a similar distribution of males and females within each group participated in the study. Self-assessed Tanner Scale stage was used to ensure participants fell into one of two categories: prepubertal (stage 1) for school aged athletes or post pubertal (stage 4 of 4) for high school aged. All participants participated in organized sports that required jumping, cutting and landing, at least three times per week. Injury prevention programs have been shown to induce favorable neuromuscular and biomechanical changes, therefore all athletes in this study did not participate in any form of injury prevention training at any time before or during data collection. Participants were excluded if they had any self-reported history of serious lower extremity musculoskeletal injury (such as ligament rupture), musculoskeletal injury within the last six months or any history of rheumatological disorder, cerebral vascular accident, peripheral nerve disorder, or any other disorder that interferes with sensory input and/or motor function. All participants were informed of testing procedures and provided written consent (or assent as appropriate) that was approved by the University’s Institutional Review Board. All testing was conducted at the Neuromuscular Research Laboratory within the University. Reliability of testing procedures has been established previously.

INSTRUMENTATION

Isokinetic strength was collected for the knee flexors and
extensors utilizing the Biodex System 3 Multi-Joint testing and Rehabilitation System (Biodex Medical Inc., Shirley, NY). Ground reaction forces during static balance testing and the single-leg stop-jump task were collected utilizing two force plates (Kistler Corporation, Worthington, OH; Model #4060-101100). Ground reaction force data was collected at 1200 Hz during the single-leg stop-jump task and at 100 Hz during the balance testing. Three-dimensional coordinate data from 15 retroreflective markers during the single-leg stop-jump task were collected and calculated using a 3D optical capture system (Peak Performance Technologies, Inc., Englewood, CO). This motion analysis system includes six high speed (120 Hz) optical cameras (Pulnix Industrial Product Division, Sunnyvale, CA) instrumented and synchronized using Peak Motus software (version 7.2, Peak Performance Technologies, Inc., Englewood, CO).

PROCEDURES

All participants completed balance assessments first, followed by strength then single-leg vertical stop jump task. Lower extremity segment lengths and joint widths of each participant were taken of the lower extremity in addition to body mass (kilograms) and standing height (meters). The Biodex System was used to test dominant leg muscle strength of the quadriceps and hamstrings musculature during an isokinetic knee flexion and extension test.19 Leg dominance was defined as the leg a participant would naturally use to kick a soccer ball. Participants were secured in the chair with straps to isolate the tested movement, range of motion was set to allow for zero to 90 degrees of rotation (based on the attachment arm); and provided a warm-up session of three repetitions at 50% of maximum effort and three repetitions at 100% of maximum effort. Participants were instructed to give maximum effort throughout the entire test. Five maximal quadriceps and hamstring contractions at 60º/sec were performed with one minute of rest between all sessions.19

Single-leg balance testing was performed bilaterally for each participant with eyes open and closed. Five trials (ten seconds each) for each condition per leg were collected. Order of testing (by condition) was determined by simple randomization prior to data collection and participants were given one practice trial for each condition and for each leg prior to testing. The testing position was unilateral stance with the untested leg flexed slightly at the hip and the knee with hands on hips. Participants were instructed to remain “as still as possible” throughout each trial and to regain the test position as quickly as possible if there is a loss of balance.20 Touchdowns on the force plate were acceptable, as they added to the variability in balance measurement. Trials were excluded if the participant touched down off the force plate because it would not be contributing to the force-platform measure.21

Fifteen retroreflective markers were utilized for data collection of 3D coordinate data during the single-leg vertical stop-jump task.22 During the single-leg vertical stop jump task, retroreflective markers were placed bilaterally over the second metatarsal head, posterior aspect of the heel, lateral malleolus, femoral epicondyle, anterior superior iliac spine, and the L5-S1 disc space. Four other markers were attached to wands (approximate length 0.07 m) and secured bilaterally with Velcro straps and athletic tape to the lateral aspect of the participant’s thigh and shank.

The single-leg vertical stop jump task consisted of the following: 1) initial starting point measured as 40% of the participant’s height from the edge of the force plates, 2) jump with a single-leg landing on a force plate, 3) immediate jump for maximum vertical height following landing on the force plate, and 4) landing in approximately the same location from which the maximal jump was initiated (Figure 1).23 Participants were given a verbal description, visual demonstration, and five practice trials on each leg in order to assure familiarity with the task. The first five good trials were used for data processing. A good trial was defined as a trial during which the participant performed the task with the proper technique, landed successfully on the force plate and did not touch down outside the force plate.

DATA REDUCTION

The Biodex Advantage Software v3.0 was used to calculate the absolute peak torque and average peak torque normalized to body weight (%BW) for the isokinetic strength test of the quadriceps and hamstrings for each leg. Additionally, the hamstring:quadriceps ratio was calculated for absolute peak torque and peak torque normalized to body weight. Single leg balance ground reaction force data were processed through a custom Matlab (MathWorks, Natick, MA) script. Ground reaction force data were passed through a zero-lag 4th order low pass Butterworth filter with a 100 Hz cutoff frequency.22 The standard deviation (SD) for each component ground reaction force (anterior-posterior, medial-lateral and vertical ground reaction force) was calculated during the entire trial and then averaged across all five static balance trials.20,21 Lower extremity kinematic and kinetic data of the single-leg vertical stop jump was calculated using Kinecalc module of the Peak Motus software package (Peak Performance Technologies, Inc., Englewood, CO). Vertical jump height was measured as the difference between the sacral marker during the static trial and the maximum during jump trial, and then calculated as percent body height (%BH). Kinematic data were calculated as previously published on reactive tasks.22 Raw analog data from the force plates were used to calculate the ground reaction force data for each vertical stop jump trial. The ground reaction force data were used to calculate the

Figure 1: Single-leg vertical stop jump task
Table 1: Subject Demographics by Sex

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<th>Female (n=78)</th>
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<td>(n=38)</td>
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<td>Females</td>
</tr>
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<td>10.47 ± 0.60</td>
<td>0.002</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.52 ± 0.11</td>
<td>1.79 ± 0.08</td>
<td>1.48 ± 0.08</td>
<td>&lt;0.101</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>44.8 ± 12.3</td>
<td>74.3 ± 6.2</td>
<td>40.2 ± 10.2</td>
<td>&lt;0.093</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

mean ± sd

Significance set at 0.05 level

peak vertical ground reaction force during the initial stance phase of the single-leg stop-jump task. This point was then identified in the joint kinematic data to determine knee flexion/extension and the knee valgus/varus angle at initial contact. Vertical stop jump peak vertical ground reaction force data were then normalized to percent body weight. Data were averaged across five trials.

STATISTICAL METHODS

All statistical analysis was performed using SPSS version 21.0 (SPSS Inc., Chicago, IL). Analyses consisted of: descriptive statistics (mean, standard deviation) for each age group and sex were calculated; independent t-tests for comparison of demographic data; two-way analysis of variance (ANOVA) to examine the effect of age group and sex on each variable; and multiple pairwise comparisons at the level of the interaction to assess differences between age group and sex. Additionally, Cohen’s $d$ effect size was calculated to assess the magnitude of difference between each pairwise comparison.

RESULTS

There were significant differences between sexes for high school athletes in height ($p<0.001$) and weight ($p<0.001$) (Table 1), with males being taller and heavier.

At the high school age, males were shown to be stronger than females in knee flexion and extension strength, both for average peak torque ($p<0.001$) and relative to body weight ($p<0.001$). (Table 2) High school aged athletes, compared to school age athletes, were stronger in knee flexion and extension strength, both for average peak torque ($p<0.001$) and relative to body weight ($p<0.001$). High school aged athletes had a larger hamstring:quadiceps ratio relative to body weight (males $p=0.031$, females $p=0.046$). Female high school ages athletes had a larger absolute peak torque hamstring:quadiceps ratio ($p=0.041$) (Table 2). School aged females demonstrated significantly better static balance than school aged males in the anterior-posterior (AP) ($p=0.047$) and the medial-lateral (ML) ($p=0.018$) directions with eyes opened and ML direction with eyes closed ($p=0.027$). High school aged females demonstrated better static balance than high school aged males, in all directions, with eyes opened and closed. (Table 3) Males exhibited better static balance at the school age, compared to high school, in the AP and ML directions with both eyes opened ($p=0.001$, $p<0.001$, respectively) and eyes closed ($p=0.001$, $p=0.001$). Whereas females only displayed better static balance at the school age in the ML direction with eyes closed ($p=0.050$). (Table 3)

Within the single-leg stop-jump task, males at the school age displayed greater peak knee flexion angle ($p=0.011$) than females. At the high school age, males demonstrated greater peak knee flexion angle ($p=0.011$) and jump height ($p<0.001$) than females. (Table 4) Both males and females performed greater jump heights at the high school age compared to school age ($p<0.001$) and males showed greater vertical ground reaction forces at the high school age ($p=0.054$). (Table 4)
Table 2: Effects of age and sex on average isokinetic knee strength

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
<th>ANOVA</th>
<th>Pairwise Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>School</td>
<td>High School</td>
<td>School</td>
<td>High School</td>
</tr>
<tr>
<td>Knee flexion average peak torque (Nm)</td>
<td>34.75 ± 12.76</td>
<td>103.26 ±</td>
<td>34.75 ± 12.76</td>
<td>103.26 ±</td>
</tr>
<tr>
<td>Knee extension average peak torque (Nm)</td>
<td>73.20 ± 21.65</td>
<td>201.66 ±</td>
<td>73.20 ± 21.65</td>
<td>201.66 ±</td>
</tr>
<tr>
<td>Average peak torque hamstring:quadriceps ratio</td>
<td>0.47 ± 0.11</td>
<td>0.52 ± 0.12</td>
<td>0.47 ± 0.10</td>
<td>0.52 ± 0.10</td>
</tr>
<tr>
<td>Knee flexion average peak torque (%BW)</td>
<td>87.09 ± 18.00</td>
<td>152.30 ±</td>
<td>87.09 ± 18.00</td>
<td>152.30 ±</td>
</tr>
<tr>
<td>Knee extension average peak torque (%BW)</td>
<td>182.90 ± 29.86</td>
<td>291.44 ±</td>
<td>182.90 ± 29.86</td>
<td>291.44 ±</td>
</tr>
<tr>
<td>%BW hamstring:quadriceps ratio</td>
<td>0.48 ± 0.10</td>
<td>0.53 ± 0.11</td>
<td>0.47 ± 0.10</td>
<td>0.52 ± 0.09</td>
</tr>
</tbody>
</table>

All measurements at 60°/s. Mean ± sd.  
BW = body weight  
p-value (F)  p-value (effect size)  Significance set at 0.05 level
Table 3: Effects of age and sex on static balance ground reaction force standard deviation in eyes open and closed conditions

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
<th>ANOVA</th>
<th>Sex Comparisons</th>
<th>Age Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>School High School School High School</td>
<td>Interaction</td>
<td>School High School Males Females</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes open - AP</td>
<td>1.72 ± 0.80 1.81 ± 0.48</td>
<td>0.112 (2.55)</td>
<td>0.047 &lt;0.001 0.001 0.084</td>
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<tr>
<td>Eyes open - ML</td>
<td>2.12 ± 1.20 2.28 ± 0.77</td>
<td>0.081 (3.09)</td>
<td>0.018 &lt;0.001 &lt;0.001 0.066</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes open - V</td>
<td>3.75 ± 2.55 2.98 ± 1.11</td>
<td>0.221 (1.51)</td>
<td>0.200 &lt;0.001 0.066 0.429</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes closed - AP</td>
<td>2.71 ± 1.57 3.67 ± 1.01</td>
<td>0.081 (3.09)</td>
<td>0.018 &lt;0.001 &lt;0.001 0.066</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes closed - ML</td>
<td>3.39 ± 3.10 5.26 ± 2.81</td>
<td>0.233 (1.43)</td>
<td>0.027 &lt;0.001 0.001 0.050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes closed - V</td>
<td>9.61 ± 6.44 8.63 ± 5.50</td>
<td>0.823 (0.05)</td>
<td>0.118 &lt;0.001 0.692 0.700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± sd</td>
<td>AP = anterior-posterior, ML = medial-lateral, V = vertical</td>
<td></td>
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</table>

Table 4: Effects of age and sex on single leg stop jump knee joint angles, jump height and vertical ground reaction force

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
<th>ANOVA</th>
<th>Sex Comparisons</th>
<th>Age Comparisons</th>
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<tbody>
<tr>
<td></td>
<td>School High School School High School</td>
<td>Interaction</td>
<td>School High School Males Females</td>
<td></td>
<td></td>
</tr>
<tr>
<td>knee flex @ IC (°)</td>
<td>13.89 ± 7.09 12.54 ± 6.62</td>
<td>0.559 (0.34)</td>
<td>0.689 0.669 0.078 0.388</td>
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<tr>
<td>knee AB/AD @ IC (°)</td>
<td>2.48 ± 3.10 2.95 ± 4.41</td>
<td>0.369 (0.81)</td>
<td>0.849 0.849 0.237 0.873</td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak knee flex (°)</td>
<td>37.39 ± 10.68 41.41 ± 9.27</td>
<td>0.619 (0.25)</td>
<td>0.011 0.011 0.916 0.072</td>
<td></td>
<td></td>
</tr>
<tr>
<td>jump height (%BH)</td>
<td>12.78 ± 16.19 16.19 ± 16.19</td>
<td>&lt;0.001 (17.67)</td>
<td>0.238 &lt;0.001 &lt;0.001 &lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak vGRF (%BW)</td>
<td>3.63 ± 0.76 3.39 ± 0.54</td>
<td>0.015 (6.03)</td>
<td>0.395 0.395 0.034 0.285</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± sd</td>
<td>IC = initial contact, vGRF = vertical ground reaction force.</td>
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DISCUSSION

Children and adolescents are subjected to a maturation process that is not linear, creating the need for periodic assessment to correctly define and change training programs. This study examined the effects chronological age and sex have on modifiable musculoskeletal and neuromuscular characteristics to help inform effective training programs. Unlike previous literature, the current study looked
at multiple variables in the same participant. The results observed in this study predominantly supported the hypotheses. Differences after maturation were seen in strength, balance, and biomechanics. These findings showed increase in strength and jump performance in both sexes and decreases in male static balance as age increased. We saw limited differences between sexes at the school age. In this study, both sexes had a significant increase in height and weight through maturation, although high school aged male athletes were on average almost 15kg heavier than their female counterpart (Table 1). With one-third of youth requiring medical attention for activity related injuries, it is essential to understand the effect of growth, development and sex related physiological differences on sports injury and performance. Development of muscular strength, balance and proper mechanics through age and sex appropriate interventions is essential for sustainable long-term athletic performance. Identifying neuromuscular differences between sexes and changes throughout maturation can help to develop specific training techniques to reduce the incidence of these injuries.

ISOKINETIC KNEE STRENGTH

Dynamic knee stability is essential in an athlete’s safety while participating in activities that require cutting, jumping, and landing. Co-contraction of the hamstring and quadriceps muscles has been found to stabilize the knee and an imbalance in hamstring to quadriceps strength may be of significance in non-contact leg injuries. The current study shows a significant increase in the ratio of hamstring-to-quadriceps strength, normalized to body weight, from the school to high school age of male and female athletes but no difference between sex. This demonstrates that while the hamstrings and quadriceps of both sexes increased with age, hamstring strength increased to a greater extent. Previous work that found significant differences in hamstring-to-quadriceps strength ratio between sex in 9-12 year old. This may be due to their participants being children recruited from local schools rather than specifically using athletes as in the current study. In young soccer athletes, an significant increase in hamstring-to-quadriceps strength ratio was seen from immature to mature females but not in males.

Moreover, knee stability is related to quadriceps and hamstring individual action at the knee; with quadriceps muscle strength playing a vital role during landing to decelerate the body and absorb impact forces and the hamstrings controlling anterior tibial translation. It has been proposed that differences in muscular strength and sex specific neuromuscular activation patterns are one reason females have a greater risk of noncontact ACL injury. The current findings agree with previous research, that absolute and body weight corrected strength gains occur in both sexes after puberty and significant differences can be seen between sexes at the high school age (Table 2). Parallel to the current findings, the Physical Activity Guidelines released from the federal government reported that both sexes significantly increase strength through maturation. Their data show adolescent boys and girls exerted significantly more pounds of force with knee extension than younger boys and girls. Similarly, significant increases in quadriceps and hamstring strength were seen with maturity in male and female soccer players. Barber-Westin et al. also found significant strength differences as chronological age increases. Thirteen-year-old female athletes were shown to have 20% greater knee extension peak torque than 9-year old, while 14-year-old male athletes had 38% greater peak torque than 9-year old. It was also found that no significant differences in knee extension or flexion peak torque exist between sexes until the age of 14 years. Male athletes between 14-17 years had significantly greater extension and flexion peak torque than their female counterparts. Data also aligns with current findings that no significant difference in strength were seen between younger girls and boys (age 6-11) for knee extension but they did find significant differences between adolescent girls and boys (age 12-15). Decrements in muscular strength have been associated with the lack of dynamic stability surrounding lower extremity joints, potentially resulting decreased balance ability.

STATIC BALANCE GROUND REACTION FORCE

Poor balance has been significantly associated with an increased risk of lower extremity injury. One measure is single leg static balance, requiring an athlete to minimize center of mass movement over a small base of support, is related to the unconscious neuromuscular control and stabilization of joints. Balance begins to emerge as a trainable motor skill from the age of 10, therefore this study evaluated static balance as a prerequisite to the additional coordination needed for dynamic balance. This study showed significant decreases in static balance in male athletes as they reached the high school age (Table 3). This may be due to the greater physical growth that occurs in males during puberty. Increases in body weight have been shown to cause a decrease in balance, due to changes in center of mass. During puberty, growth changes may happen at a faster rate than the visual, vestibular and somatosensory systems can adapt. Increases in body weight, without increase in neuromuscular control, may be the cause of the disturbances in equilibrium seen in high school aged males. To decrease risk of injury in male athletes during and after puberty, prophylactic balance training may lead to task-specific neural adaptations. Additionally, training to improve balance can decrease risk of injury by enhancing agonist-antagonist muscle co-contractions which increases joint stiffness, and stabilizing joints against perturbations. Similar to knee stability, balance requires swift and constant feedback from visual, vestibular and somatosensory systems for coordinated movement to maintain balance. This study shows that female athletes have significantly better medial-lateral stability at both age groups (Table 3). All static balance measures were also significantly different between sexes in the high school age group. These results may be due to a lower center of gravity in females compared to males. While not assessed in this study, if females had smaller and lighter upper body with larger and heavier lower body, compared to males, this would increase the stability of their center of gravity. A difference in static balance at the high school age compared to females and to males at the school age may also be the result of increased
proper biomechanics during landing can affect the GRF values for both sexes. In the current study, there were no differences between sexes at each age group; however, some findings related to the speed to attenuate forces when landing. Lack of differences between sexes at each age group may be related to the increase in GRF levels in participants. This study did not show significant sex differences in GRF during landing to be greater in female athletes as compared to males. This led to a more upright posture to maximize energy absorption at the hip and ankles. The current study did not find significant sex differences in knee flexion and abduction/adduction angle at initial contact in both the school aged and high school aged groups. Again, these results are similar to Yu et al. who also found that female youth soccer players had decreased knee flexion angles during a stop-jump task. Yet these results are different from previous findings that show knee valgus angle during landing to be greater in female athletes as compared to males.

Increased vertical GRFs in males at the high school age may be related to increased testosterone levels in males. Following puberty, males have 15 times higher circulating testosterone concentration than in females. The biological effects of elevated testosterone include larger muscle mass and stiffer connective tissue, allowing males to exert greater muscular force more rapidly. However, this study did not assess hormone or associated hemoglobin levels in participants. This study only showed significant differences in peak vertical ground reaction forces (GRF) between school-aged and high school aged male athletes. Increased vertical GRFs in males at the high school age may be due to the larger increase in vertical jump height. Although jump height significantly increased at the high school age for both sexes, on average, males jumped 8 inches higher than their school age counterparts, while females only jumped 4 inches higher. No difference in vertical GRF was found between sexes at the school or high school age. This differs from Pappas et al. who found females to have greater vertical GRF during jump tests than is found in male athletes. However, current results are similar to previous research that found no vertical GRF difference between sexes, but did report differences in rate of loading in which females reached vertical GRF 20% faster than males. It was proposed that decreased knee flexion and neuromuscular response reduces the ability of females to attenuate forces when landing. Lack of differences between sexes at each age group may be related to the speed in which participants decelerated, which was not assessed in the current study. These findings of no differences between sexes in knee kinematics at initial contact may also be associated with similar GRF values for both sexes.

Single-leg landings occur frequently in physical activity and sports. Proper biomechanics during landing can affect ground reaction force and loading of lower extremity structures, in turn preventing lower limbs injuries. This study showed no significant difference for either sex through maturation for knee flexion and abduction/adduction angles at initial or peak knee flexion angle during a single leg vertical stop jump task. This is partially similar to Yu et al. who found no difference between ages for knee flexion angle at initial contact or peak flexion angle in male soccer players during a stop-jump task. However, they did find significant decrease in both knee flexion angles for female soccer players as they aged. Initiating neuromuscular training in females at a younger age may help develop optimal movement strategies and mitigate the effects of puberty on dynamic control. As knee flexion angle increases, tensile stress on the ACL due to quadriceps muscle contraction has been shown to decrease. Neuromuscular training to develop hamstring and quadriceps co-contraction may protect the lower extremity during sport related movements. Significantly smaller peak knee flexion angles in females show the need for safe landing strategies, increasing knee flexion angle, at all ages. This may be related to muscle loading, which was not assessed in the current study. Decker et al. reported greater knee extensor and ankle plantarflexor energy absorption in females during drop jumps. This led to a more upright posture to maximize energy absorption at the hip and ankles. The current study did not find significant sex differences in knee flexion and abduction/adduction angle at initial contact in both the school aged and high school aged groups. Again, these results are similar to Yu et al. who also found that female youth soccer players had decreased knee flexion angles during a stop-jump task. Yet these results are different from previous findings that show knee valgus angle during landing to be greater in female athletes as compared to males. Increase in female knee valgus angles found in their study may be associated with the increase in female vertical GRF also seen in their study, neither of which were observed in the current study.

The current study had limitations, including the small sample size for each sex in the school aged and high school groups. Tanner staging by a trained health care professional has long been the medical standard. Therefore this study only included participants who self-assessed within stage 1 or stage 4 to reduce the chance of miscategorization. Additionally, athletes in this study did not participate in the same sport, but all athletes did participate in sports that require jumping, cutting and landing (ie: soccer or basketball) to represent the types of sports in which non-contact ACL injury can occur. Activity frequency was a component of inclusion criteria to ensure athletes had similar general conditioning for knee flexion and abduction/adduction angles at initial contact. This is partially similar to Yu et al. who also found significant decrease in both knee flexion angles for female soccer players as they aged. Initiating neuromuscular training in females at a younger age may help develop optimal movement strategies and mitigate the effects of puberty on dynamic control. As knee flexion angle increases, tensile stress on the ACL due to quadriceps muscle contraction has been shown to decrease. Neuromuscular training to develop hamstring and quadriceps co-contraction may protect the lower extremity during sport related movements. Significantly smaller peak knee flexion angles in females show the need for safe landing strategies, increasing knee flexion angle, at all ages. This may be related to muscle loading, which was not assessed in the current study. Decker et al. reported greater knee extensor and ankle plantarflexor energy absorption in females during drop jumps. This led to a more upright posture to maximize energy absorption at the hip and ankles. The current study did not find significant sex differences in knee flexion and abduction/adduction angle at initial contact in both the school aged and high school aged groups. Again, these results are similar to Yu et al. who also found that female youth soccer players had decreased knee flexion angles during a stop-jump task. Yet these results are different from previous findings that show knee valgus angle during landing to be greater in female athletes as compared to males. Increase in female knee valgus angles found in their study may be associated with the increase in female vertical GRF also seen in their study, neither of which were observed in the current study.

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CONCLUSION

There are a number of factors unique to the adolescent athlete during the period of growth and maturation that have the potential to increase injury risk. Examination of neuromuscular and biomechanical sex differences throughout growth and maturation may help identify risk factors that lead to injury rate differences. By assessing multiple factors within an individual participant, the current study gives a more comprehensive assessment of the athlete. This study showed significant increase in strength from school age to high school age in both sexes and that male athletes were significantly stronger at the high school age. Static balance was significantly better in male athletes at school age compared to high school aged. At the high school age, female athletes demonstrated significantly better static balance. Vertical stop jump height increased from the school age to the high school age in both sexes and peak knee flexion angles were greater in male athletes at both the school and high ages. Fitness and skill development occur on a constantly changing base of physical growth and biological maturation; these processes occur simultaneously and interact with each other and the demands of sport. It is important to understand how the role of sex and maturation influence athletic development for the most effective injury prevention and performance programs.

CONFLICTS OF INTEREST

The authors report no conflicts of interest related to this manuscript.

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REFERENCES


Original Research

Functional Movement Screen Detected Asymmetry & Normative Values Among College-Aged Students

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Keywords: movement system, injury prevention, injury risk factors, functional test

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Background

The Functional Movement Screen (FMS™) is a popular test used by sports medicine professionals to identify dysfunctional movement patterns by analyzing mobility and stability during prescribed movements. Although the FMS™ has been a popular topic of research in recent years, normative data and asymmetries in college-aged students have not been established through research.

Purpose

The objective was to determine normative FMS™ scores, report frequency counts for FMS™ asymmetries, and determine if the number of sports seasons and number of different sports an individual participated in during high school varied between university students that showed FMS™ identified asymmetries.

Study Design

Cross-sectional Study

Methods

One hundred university students completed the FMS™ and an associated survey to determine which sport(s) and for how many seasons they participated in each sport(s) during high school. Total FMS™ scores were assessed as well as identifying the presence of an asymmetry during a FMS™ screen. An asymmetry within the FMS™ was defined as achieving an unequal score on any of the screens that assessed right versus left movements of the body.

Data Analysis

Data analysis included descriptive statistics, Pearson correlation was utilized to investigate the relationship between number of sports played and number of sport seasons. Shapiro Wilk test for normality, and Mann Whitney U test was employed to investigate group differences in number of sports played. All analyses were conducted using SPSS software.

Results

Statistically significant correlations (r = .286, r² = .08, p < 0.01) were found for both number of sport seasons and number of sports with FMS™ total score. In addition, participants without FMS™-detected asymmetries played significantly more seasons and more sports than their peers that presented asymmetries (U = 946.5, z = -1.98, p = 0.047). Finish with the actual p-value in parenthesis.

Corresponding Author: Craig Triplett School of Behavioral Sciences, Black Hills State University 1200 University St, Unit 9405, Spearfish, South Dakota 57799. Email: craig.triplett@bhsu.edu, Office Phone (605) 642-6169.
Conclusion
Participating in multiple sports and multiple sport seasons during high school was associated with higher FMS™ total scores. Results suggest that participating in multiple sports and multiple sport seasons was associated with fewer asymmetries, which may decrease subsequent injury risk.

Level of Evidence
3b

INTRODUCTION
A popular topic of sports medicine and performance enhancement research has been the pre-participation or pre-season athletic screen. Screens are often performed prior to the commencement of a training program or sport season to identify muscle imbalances, weaknesses, or movement patterns that may increase an individual’s risk for injury.1–7 Various methods have been used to identify asymmetries in athletes. Muscular strength asymmetries and balance have been a popular topic of research, and further investigation is warranted.8–17

The Functional Movement Screen (FMS™) is a screening tool used to identify dysfunctional movement patterns. The assessment consists of seven individual tests (deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability) which are scored on a scale from 0–3, with a possible composite score of 21 (higher scores indicative of better movement competence).18,19 Of the seven individual FMS™ tests, five compare the right side to the left side (hurdle step, in-line lunge, shoulder mobility, active straight leg raise, and rotary stability). This comparison allows for asymmetries, if present, to be identified. A participant may score a 3 on the right side, while scoring a 1 or 2 on the left side. When there is an asymmetry that occurs, the lower of the two scores is recorded for that individual test. If pain is present during the screen, the subject is scored as a 0 for that particular sub-test.18,19 The FMS™ has been used to predict injury risk and performance outcomes across populations, including professional American football players,20,21 elite track and field athletes,22 Marine officer candidates,23 adolescent children,24 young active adults,25 high school baseball players,26 junior and high school ice hockey players,27 high school athletes,28 and female collegiate athletes.29 Research involving professional American football players has identified individuals scoring lower than a 14 on the FMS™ are 11 times more likely to become injured than individuals scoring greater than or equal to 15.30 This research was one of the first to establish a cut-off score for injury risk using the FMS™. A recent meta-analysis has indicated there is conflicting evidence regarding the specific cut-off score used to predict injury risk.30 There are relatively few studies supporting the notion that individuals scoring lower than a 14 on the FMS™ are more likely to become injured than individuals scoring greater than or equal to 15.30 Thus, it appears that comparing the FMS™ composite score of an individual to a cut-score and associated injury risk is in question at the present time. Due to the conflicting nature of the previous research examined in the meta-analysis, additional research needs to be completed to examine the application of FMS™ scores for injury risk prediction.

One area of interest that has drawn limited research attention is the relationship between asymmetries identified during FMS™ testing and injury rates with participation in sport. Research on American football players with an FMS™ detected asymmetry had a 1.8 times greater risk for injury than those without an asymmetry.21 A 2016 study examined total FMS™ scores and the presence of asymmetries in NCAA Division II athletes and found that those with an asymmetry or individual test score of 1 were 2.73 times more likely to sustain an injury.31 A study performed with 237 elite junior Australian football players, identified that if participants demonstrated one or more asymmetry, they experienced a moderate increase in their risk of injury (hazard ratio = 2.2 relative risk = 1.9; p = 0.047). Additional analysis identified that the presence of two or more asymmetrical sub-tests was associated with an even greater increase in risk of prospective injury (hazard ratio = 3.7; relative risk = 2.8; p = 0.005).32 As such, asymmetries discovered during FMS™ testing may be useful in predicting injury risk in successive sport participation.

Despite these findings, no research has examined the effect of previous athletic participation on an individual’s performance on the FMS™, specifically identification of asymmetries. Therefore, the objective was to determine normative FMS™ scores, report frequency counts for FMS™ asymmetries, and determine if the number of sports seasons and number of different sports an individual participated in during high school varied between university students that showed FMS™ identified asymmetries. Since the FMS™ examines mobility and stability in multiple planes of movement, the researchers hypothesized that the various biomechanical demands of playing multiple sports may lead to fewer FMS™ asymmetries.

METHODS
STUDY DESIGN
This study employed a retrospective analysis examining if the number of sport seasons and number of sports participated in high school was different between university students who had symmetrical or asymmetrical movements during FMS™ testing. Prior to the FMS™ testing, each participant completed a written questionnaire that included age, which school-sponsored high school varsity sport(s) the participant played in high school, and how many seasons the participant played each sport. At the time of study, participants were engaged in moderate-to-vigorous group exercise sessions each week as part of a university wellness class. Participants were excluded from the study if they had...
any injuries preventing them from engaging in the class exercise sessions.

PARTICIPANTS

A convenience sample of 100 healthy participants (57 females, 43 males) between 18 and 26 years of age \( (\text{mean} \pm \text{SD} = 19.5 \pm 1.7 \text{ years}) \) were recruited from a university-level introductory wellness class. Participants included in the study participated in regular physical activity as part of the university wellness class, which consisted of two structured moderate-to-vigorous group exercise sessions each week. Any additional exercise performed by the participants outside of the university class was not assessed. Exercise sessions were a combination of circuit resistance training and cardiovascular exercise. Exclusion criteria included: any reported recent (within the prior six weeks) musculoskeletal or head injuries that may have affected their overall performance on the \textit{FMS}™, which was assessed by a questionnaire. All participants provided written informed consent prior to completing the questionnaire and participating in the \textit{FMS}™ screening. The study was approved in advance by the Institutional Review Board.

PROCEDURES

The lead researcher was blinded to questionnaire results until after \textit{FMS}™ testing was completed. The \textit{FMS}™ has demonstrated acceptable interrater and intrarater reliability, with interrater test-retest intraclass correlation coefficients (ICC) at 0.6, and intrarater ICC at 0.946. Interrater reliability (Kappa) for individual test components of the \textit{FMS}™ has demonstrated moderate to excellent agreement \( (0.40-0.95).^{33–35} \) All scoring was performed by the \textit{FMS}™ Level 1 Certified lead researcher. The participants were asked to wear their usual workout clothing and athletic shoes. Each participant performed each of the seven tests (deep squat, hurdle step, in-line lunge, shoulder mobility, active straight-leg raise, trunk stability push-up, and rotary stability) three times.\(^{18,19} \) Each time the participant performed each of the seven tests, they were scored on a scale of 0 to 3.\(^{18,19} \) A score of 0 indicated that the participants reported pain during the performance of the specific test. A score of 1 indicated a failure to complete the test or a loss of balance during the test. A score of 2 indicated completion of the test, but with a movement compensation. A score of 3 indicated completion of the test, without a movement compensation. For each of the seven tests, the highest score of the three trials was given to the participant. For the tests with a bilateral assessment component (hurdle step, in-line lunge, shoulder mobility, active straight-leg raise, and rotary stability), the side with the lowest score was used for data analysis. An asymmetry within the \textit{FMS}™ was defined as achieving an unequal score on any of the tests that assessed right versus left movements of the body. If an asymmetry was present, the researchers recorded it along with the participants’ total \textit{FMS}™ score. The sum of the seven assessments provided an overall maximum score of 21. Three of the tests (shoulder mobility, trunk stability push-up, and rotary stability) within the \textit{FMS}™ also have a clearing procedure associated with them. For each of the clearing procedures, the participant was given a positive if they reported pain during the clearing procedure or a negative if they reported no pain during the clearing procedure. Total \textit{FMS}™ scores and number of asymmetries were calculated and compared to the results on the questionnaire for each participant for statistical analysis.\(^{18,19} \)

STATISTICAL ANALYSIS

Statistical analysis was conducted using IBM SPSS version 24 (IBM Corp., Armonk, NY). Summary analysis, Pearson correlation was utilized to investigate the relationship between number of sports played and number of sport seasons. Shapiro Wilk test for normality, and Mann Whitney \textit{U} test was employed to investigate group differences in number of sports played with a priori alpha established at 0.05.

RESULTS

One hundred college-age study participants participated in the analysis including 43 males and 57 females. The study group \( (n=100) \) participated in diverse sports and a variety of sport seasons. \textit{FMS}™ scores of the study participants ranged from 7 to 19 with the highest frequency scoring 16 \( (n = 19) \) on the \textit{FMS}™. The mean score for the study sample was 14.40. \textit{FMS}™-detected asymmetry was observed in 57 of the 100 study participants (28 males, 29 females) with multiple asymmetries occurring in 22 participants. Of the 57 participants with at least one detected asymmetry, nine were identified during the \textit{FMS}™ hurdle step, 24 in the lunge, 25 in shoulder mobility, 10 in straight leg raise, and 18 in rotary stability.

Shapiro-Wilk test was conducted to examine the normality of the distribution of \textit{FMS}™ scores. The distribution for all \textit{FMS}™ scores was found to be non-normal \( (p=0.05) \). Pearson correlation analysis revealed a statistically significant relationship between the number of sports played \( (r = .286, r^2 = .08, p < 0.01) \) and \textit{FMS}™ total score. While statistically significant, the number of sports accounted for only 8% of the variability in \textit{FMS}™ total score. Independent samples Mann-Whitney \textit{U} test was conducted to evaluate whether the number of sports were lower, on average, for participants with an \textit{FMS}™ detected asymmetry compared to those participants without and \textit{FMS}™ detected asymmetry. Results indicated that participants without an \textit{FMS}™ detected asymmetry played three sports as opposed to two sports for participants with a detected asymmetry \( (U = 946.5, z = -1.98, p = 0.047) \), thus rejecting the null hypothesis (see Figure 3). Participants who did not display asymmetries played more sports than their counterparts with asymmetries. Combined with the correlational analysis between number of sports and number of sport seasons, data appeared to indicate that movement variety is related to improved \textit{FMS}™ total score and reduced asymmetries.

DISCUSSION

The objective was to determine among university students normative \textit{FMS}™ scores, report frequency counts for \textit{FMS}™ asymmetries, and determine if the number of sports sea-
Figure 1: Number of unique sports played. Participants (N = 100) were asked to indicate the number of sports played. Three sports was most frequently selected (n = 26), while only two participants played five different sports. Almost two-thirds of the study group participated in two or more sports and 43% of the participants participated in three or more sports (mean = 2.06, SD = 1.41).

The mean FMS™ score of the current sample of 100 college-age students was 14. Other studies have reported mean FMS™ scores in active participants ranging from 13–16.2,25,36–38 While the sample mean was consistent with other reported data, it is important to note that the samples vary in demographic characteristics. Although many in the current study reported a history of sport participation, data was not collected on the sample’s current physical activity level or their present status as a collegiate athlete.

In the current study sample of 100 participants, the FMS™ detected at least one asymmetry in over half of the population (n = 57). While research has examined the possible association of FMS™-detected asymmetry and subsequent injury,31 minimal research was found that attempted to establish normative data for the prevalence of FMS™ detected asymmetry in a population of recreationally active college age adults.25

While a low, statistically significant relationship between both the number of different sports played and total FMS™ score was found, the number and different sports played could only explain a small part (8%) of the total FMS™ score. This is potentially related to the size of the study group, which limits the applicability of this finding without further investigation. There was a significant difference between the number of different sports played and whether FMS™ asymmetries existed, but the clinical significance of this remains unknown. Together, these results support the notion of increased levels of physical activity and the various biomechanical demands of different sports may lead to improved functional movement. Prior research has demonstrated that higher levels of exercise participation were associated with higher FMS™ scores.39 The results of this research highlight that not only does the level of activity influence functional movement, the diversity of movement through various sports may also play a role.

The current research may support current efforts by researchers examining the impact of single sport participation in young athletes. Literature suggests that those athletes who play one single sport or engage in year-round training longer than eight months per year have an increased risk of injury, burnout, and a loss in developing lifetime sport skills.40,41 The results show that those students who participated in varying sports were more likely to have higher functional movement screen scores and fewer asymmetries. This supports the notion that young athletes participating in more sports may improve movement quality. The authors offer this interpretation with caution as the study was not specifically designed to assess the effect of sport specialization on FMS™ scores. Future research should examine this relationship specifically.

LIMITATIONS

One of the limitations of this study was that the amount of time that had passed since each participant graduated high school was not controlled. The average age of study participants was 19.5 years (range 18–26 years) and suggests that most study participants may not have been far removed from high school sport participation, however some had not
Figure 2: Number of sports seasons played. Participants (N = 100) were asked how to indicate the number of sports seasons they played. For example, a participant could have played basketball in three different seasons and baseball in one season, for a total of four seasons. In this case, the greatest frequency belonged to non-athletes, while 15 seasons included the fewest participants. Sport seasons participation was more than three times the average number of sports (mean= 6.49, SD = 4.79) indicating, on average, that study participants were practicing a single sport for multiple seasons.

Figure 3: Comparison of number of different sports played (DV) based on FMS™ detected asymmetry (IV). Independent samples Mann-Whitney U test revealed that participants without an FMS™ detected asymmetry played a greater number of sports (U = 946.5, z = -1.98, p = 0.05), indicated by a median difference of one sport.

Figure 5: Comparison of number of different sports played (DV) based on FMS™ detected asymmetry (IV). Independent samples Mann-Whitney U test revealed that participants without an FMS™ detected asymmetry played a greater number of sports (U = 946.5, z = -1.98, p = 0.05), indicated by a median difference of one sport.
participated for multiple years. Another limitation of the study is that previous musculoskeletal injuries or surgeries were not assessed. Additionally, the researchers did not determine specific sport specialization. Finally, although all participants were engaged in two structured moderate-to-vigorous group exercise sessions each week as part of their university wellness class, physical activity frequency and intensity outside of class was not assessed. Some of the participants may have also been engaged in physical activity outside of the university wellness class, such as participating in club or recreational sports.

CONCLUSION

The results of the current study indicate that individuals that played more than one sport and for multiple sport seasons exhibited improved symmetry in their performance on the FMS™. This is important in that it demonstrates that college aged students who participated in a wider variety and in an increased volume of sport activities in high school were less likely to have FMS™-detected asymmetrical dysfunction in their movement patterns in college. Current sport culture tends to emphasize sport specialization; however, encouraging athletes to engage in more than one sport may reduce their likelihood of FMS™-detected asymmetry. Having athletes participate in various sports may contribute to more symmetrical movement performance and minimize injury risk throughout their careers. Coaches, athletic trainers, and strength and conditioning specialists at any level may benefit from gathering data on their athletes to understand how past participation in sports may affect current performance, movement quality, and injury risk. Identifying asymmetries early may also assist coaches and athletic trainers in customizing training programs to reduce athletes’ injury risk and asymmetrical function.

CONFLICTS OF INTEREST

The authors do not have any conflicts of interest to report.

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Original Research

A Preseason Training Program With the Nordic Hamstring Exercise Increases Eccentric Knee Flexor Strength and Fascicle Length in Professional Female Soccer Players

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Background
Training programs that include the Nordic hamstring exercise (NHE) have been shown to increase eccentric knee flexor strength and biceps femoris fascicle length in male athletes. However, the effect of NHE on female athletes remains unknown.

Purpose
To investigate the collective and individual responses of professional female soccer players engaged in a preseason training program with the NHE regarding eccentric knee flexor strength and biceps femoris long head fascicle length.

Study Design
Quasi-experimental study.

Methods
Sixteen amateur female soccer players (without a NHE training routine) were evaluated 8-weeks apart to: (1) assess reliability of eccentric knee flexor strength and biceps femoris fascicle length measures; and (2) determine the typical error of measures that would be used to discriminate training responders and non-responders. The NHE training group had 17 professional female soccer players who performed an 8-week training program with the NHE during preseason. Within-group analysis was performed with paired sample t-tests (pre- vs. post-training), and individual responses were determined using the typical error criteria.

Results
The non-trained group's data demonstrated that measures of strength (ICC=0.82-0.87, typical error = 12-13 N) and fascicle length (ICC=0.92-0.97; typical error = 0.19-0.38 cm) were reliable. In the NHE training group, both limbs increased the eccentric knee flexor strength (~13%; ES=0.74-0.82) and the biceps femoris fascicle length (~6%; ES=0.44-0.65). Twelve players (~71%) were considered responders to the NHE training program for the eccentric knee flexor strength, while eight athletes (~47%) were responders for the biceps femoris fascicle length.

Conclusion
The 8-week preseason training program with the NHE increased both eccentric knee flexor strength and biceps femoris fascicle length in professional female soccer players. More than two-thirds of players demonstrated a meaningful increase in eccentric strength, while nearly half achieved consistent fascicle length increases with the NHE training.

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INTRODUCTION

Top-level male soccer players present injury rates of 4.1/1.000 hours of training exposure and 27.5/1.000 hours of match exposure, while injury rates in female players are 2.7–3.1/1.000 hours and 13.9–25.6/1.000 hours in training and matches, respectively. According data from 2016–2017 season, English Premier League male clubs suffered an average of 1410 days out due to injury and lost £45 million per season due to injury-related decrements in performance. The extent of the injury-related losses is not yet clear in the context of female professional soccer, but there is no doubt that injury prevention is a current priority of soccer medicine in both sexes.

Sport injuries are complex and multifactorial in nature, so the prevention strategies require a multidimensional approach, which includes specific exercises to enhance muscle strength, joint mobility, neuromuscular control, and movement efficiency, as well as other strategies (e.g., workload monitoring). Understanding of injury mechanisms and identification of potential risk factors play a key role on preventing strategies in sports. Therefore, soccer clubs apply a range of tests for screening intrinsic risk factors and employ specific strategies to minimize the injuries’ incidence and/or burden.

The hamstring strain injury is one of the most prevalent injuries in team sports, including soccer. Up to 80% of hamstring injuries in soccer occur during high speed running. While direct evidence is still lacking, the majority of the literature suggests that the most likely timing of injury is the late swing phase, characterized by peak musculotendon strain and negative work. Low eccentric knee flexor strength is traditionally pointed out as a risk factor for hamstring injuries, which have been supported by prospective studies with soccer players, as well as with athletes from other sports. More recently, a prospective study evidenced that players with short fascicles in the biceps femoris long head (BF\textsubscript{LH}) are also more likely to sustain hamstring injury. All these studies have only focused on outcomes for male athletes. However, it seems reasonable that prevention programs for both sexes should address strategies to increase the eccentric knee flexor strength and BF\textsubscript{LH} fascicle length.

The Nordic hamstring exercise (NHE) is a field-based exercise with focus on eccentric action of knee flexor muscles. The NHE was included in the injury prevention program developed by the Fédération Internationale de Football Association (FIFA), the “FIFA 11+”, and has been consolidated as one of the commonly used strategies to prevent hamstring injuries in top-tier soccer clubs. A recent systematic review including male and female athletic populations supports that teams using injury prevention programs that included the NHE reduces hamstring injury rates by half. This preventive effect seems to be related to increases on both eccentric knee flexor strength and BF\textsubscript{LH} fascicle length. However, no study has evaluated whether NHE promotes such muscular adaptations in female soccer players. Therefore, the aim of this study was to investigate the collective and individual responses of professional female soccer players engaged in a preseason training program with the NHE regarding eccentric knee flexor strength and BF\textsubscript{LH} fascicle length.

METHODS

STUDY DESIGN

A group of amateur female soccer players (without a NHE training routine) was recruited and evaluated twice within an 8-week interval. These data were used to: (1) assess the reliability of measures collected in this trial; and (2) determine the typical error of measures that would be used to discriminate responders and non-responders in the NHE training group. In the NHE training group, professional female soccer players completed an eight-week NHE training program coinciding with the club preseason. The participants’ randomization into experimental and control groups was not possible due to the club requirement that all players should perform the preventive program using the NHE. Evaluations were performed one week before starting and one week after ending the training program.

The Ethics Committee of the Federal University of Health Sciences of Porto Alegre (Porto Alegre, Brazil) approved the present study. All subjects were informed about the study purpose and procedures, and provided written informed consent to participate.

PARTICIPANTS

Sixteen amateur female soccer players were part of the non-trained group. They were recruited through the dissemination of the study on social media and played soccer at least once a week. The NHE training group had 17 professional female soccer players from a Brazilian first national division team. They were engaged in a five-day weekly training routine, and one to two weekly games per week. Characteristics of participants are expressed in Table 1.

The following inclusion criteria were adopted: (1) age between 18 and 40 years of age; (2) absence of thigh muscle injuries in the six months prior to the study; (3) absence of musculoskeletal injuries in lower limbs during data collection; (4) absence of any health disorders that would interfere with the NHE execution. Participants allocated in the NHE training group had to have attended a minimum of 14 training sessions (i.e., ~90% adherence) to be included in data analysis, while participants allocated in the non-trained group should have kept their usual exercise routine between the two evaluation time-points. All participants were instructed not to consume any stimulant substance, medicine or alcoholic beverages in the 24 hours before the testing sessions.

PROCEDURES

FASCICLE LENGTH EVALUATION

A B-mode ultrasonography system (DP-30, Mindray Medical International Ltd., Shenzhen, China) with a linear array probe (53 mm) was used to assess muscle architecture parameters of the BF\textsubscript{LH}. All ultrasound scans were taken by an experienced researcher through methods routinely used in our laboratory. The participants were assessed in prone...
Table 1: Characteristics of participants (mean±SD).

<table>
<thead>
<tr>
<th></th>
<th>Non-trained group (amateur players)</th>
<th>NHE training group (professional players)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>24±4</td>
<td>24±5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>61±4</td>
<td>58±6</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.64±0.04</td>
<td>1.62±0.04</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>22.74±1.79</td>
<td>22.00±2.16</td>
</tr>
</tbody>
</table>

position with the hips neutral, the knees fully extended, and the muscles relaxed. Ultrasonography scans were taken at 50% of the muscle length (i.e., the midportion between the ischial tuberosity and the superior border of the fibular head). The ultrasound probe was positioned perpendicularly to the skin and following the longitudinal axis of the BF_LH with slight adjustments in probe orientation as necessary to optimize identification of the aponeuroses and fascicles.

Three ultrasound images of each limb were obtained and stored for analysis through the ImageJ software (National Institutes of Health, EUA). Image analysis was performed by an assessor blinded to group allocation. The most visible fascicle in each image was used to estimate the BF_LH fascicle length using a validated equation. The average value between the three ultrasound images was used for statistical analyses. Previous data collected in our lab in 20 healthy active men presented acceptable test–retest reliability scores for BF_LH fascicle length [intraclass correlation coefficient, 0.95 (0.86–0.98); coefficient of variation, 5.5% (4.0–9.2%); typical error, 0.48 cm (0.35–0.79)]. The non-trained group's data were used to assess the test-retest reliability in female soccer players in the current study.

**ECCENTRIC STRENGTH EVALUATION**

The eccentric knee flexor strength during the NHE execution was measured through a custom-made device (Figure 1). This device is similar to the prototype developed by Opar et al., and has been used in studies with male soccer players. Previous data collected in our lab consisting of 20 healthy active men presented acceptable test–retest reliability scores for knee flexor strength [intraclass correlation coefficient, 0.94 (0.85–0.98); coefficient of variation, 5% (5.2–6.7%); typical error, 18.54 N (13.93–22.36 N)]. The non-trained group's data were used to assess the test-retest reliability in female soccer players in the current study.

Briefly, the participant was positioned to perform the NHE on a platform, and commercially available load cells (E-last; E-sporte Soluções Esportivas, Brasilia, Brazil) with simultaneous transference of data via Bluetooth were fastened around their ankles (right above the lateral malleolus). The participant was instructed to execute the NHE as the following: from the initial position (kneeling, the hip neutral and the torso upright), lay the torso forwards using only the knee joint (e.g., without altering the position of hips or spine), in slow speed and using the hamstring muscle eccentrically during the entire range of motion to avoid the torso acceleration to the floor. The participant should have to use their upper limbs to absorb the fall and to return to the initial NHE position. Each participant performed five NHE repetitions, with a 10-second rest between attempts. The force values were continuously registered during all repetitions, and the highest force value obtained in each lower limb was considered to statistical analysis.

**NHE TRAINING PROGRAM**

The 8-week NHE training program (frequency and number of sets and repetitions) was based on previous studies involving NHE and provided a progressive workload increase (Figure 2). The NHE training weekly schedule was set by the coaching staff according to the games and travels, always respecting at least 48 hours between the NHE training sessions. NHE was always performed before soccer practices. A regular warm-up protocol guided by the team strength and conditioning coach was performed before the NHE execution. Players with similar anthropometric characteristics were organized in pairs to perform the NHE. A researcher supervised every NHE session to ensure correct implementation and the training volume (number of sets and number of repetitions per set) as well as proper exercise.
Table 2: Reliability of eccentric knee flexor strength and biceps femoris long head fascicle length measures. Data collected in non-trained group [mean±SD (95%CI)].

<table>
<thead>
<tr>
<th>Measure 1</th>
<th>Measure 2</th>
<th>ICC</th>
<th>CV</th>
<th>TE</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eccentric strength (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right limb</td>
<td>235±35 (217-254)</td>
<td>235±32 (227-260)</td>
<td>0.87</td>
<td>5%</td>
<td>12.74 N</td>
</tr>
<tr>
<td>Left limb</td>
<td>230±29 (215-244)</td>
<td>235±24 (223-248)</td>
<td>0.82</td>
<td>5.3%</td>
<td>11.97 N</td>
</tr>
<tr>
<td>Fascicle length (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right limb</td>
<td>9.43±1.86 (8.47-10.39)</td>
<td>9.46±1.71 (8.58-10.34)</td>
<td>0.97</td>
<td>3.8%</td>
<td>0.19 cm</td>
</tr>
<tr>
<td>Left limb</td>
<td>9.78±1.28 (9.12-10.44)</td>
<td>9.93±1.21 (9.31-10.55)</td>
<td>0.92</td>
<td>4.2%</td>
<td>0.38 cm</td>
</tr>
</tbody>
</table>

N, Newtons, cm, centimeters, ICC, intraclass correlation coefficient; CV, coefficient of variation; TE, typical error.

Figure 2: Left: players performing the Nordic hamstring exercise (NHE); Right: the NHE training program.

STATISTICAL ANALYSIS

Data collected in non-trained group (amateur players) were used to assess intraclass correlation coefficient (ICC), typical error (TE) and coefficient of variation (CV) of the measures. ICC values were qualitatively recorded as poor (<0.50), moderate (0.50-0.74), good (0.75-0.90), and excellent (>0.90). Additionally, a CV of 10% or less was set as the level at which a measure was considered reliable.

In the NHE training group, paired sample t-tests were used to check difference between pre- and post-training in each limb. The significance level was set as 5% (α<0.05). Effect size (ES) calculation was performed using the Cohen's d. Training effects were considered as "trivial" (ES<0.2), "small" (ES>0.2), "moderate" (ES>0.5) or "large" (ES>0.8).

The between-limbs average change (pre- to post-training) was used for calculation of individual responsiveness to NHE training. Responders and non-responders were determined using the typical error criteria: non-responders were defined as subjects who failed to achieve an increase that was greater than two times the typical error (TE) of measurement.

RESULTS

The non-trained group's data demonstrated that the measures used in this study were reliable (Table 2). All participants in the NHE training group attended 16 sessions (i.e., 100% adherence). The group experienced significant increases (p<0.05) in both lower limbs for the eccentric knee flexor strength (moderate to large effect sizes) and BF_LH fascicle length (small to moderate effect sizes), as detailed in Table 3. Twelve players (~71%) were considered responders to the training program for the eccentric knee flexor strength, while eight athletes (~47%) were responders for the BF_LH fascicle length (Figure 3). The five non-responders for the eccentric knee flexor strength were also non-responders for the BF_LH fascicle length.

DISCUSSION

This is the first study to investigate the effects of a NHE training program on hamstring injury risk factors in professional female soccer players. The main findings were that...
Table 3: Eccentric knee flexor strength and biceps femoris long head fascicle length of the NHE training group [mean±SD (95%CI)].

<table>
<thead>
<tr>
<th></th>
<th>Pre-training</th>
<th>Post-training</th>
<th>Δ</th>
<th>Δ%</th>
<th>ES</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eccentric strength (N)</strong></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Right limb</td>
<td>263±41 (242-284)</td>
<td>298±48 (274-323)</td>
<td>35.31</td>
<td>13.41</td>
<td>0.82C</td>
<td>0.003</td>
</tr>
<tr>
<td>Left limb</td>
<td>254±44 (231-276)</td>
<td>289±53 (261-316)</td>
<td>34.9</td>
<td>13.76</td>
<td>0.74B</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Fascicle length (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right limb</td>
<td>9.90±1.44 (9.16-10.64)</td>
<td>10.51±1.45 (9.76-11.26)</td>
<td>0.61</td>
<td>6.16</td>
<td>0.44A</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Left limb</td>
<td>9.57±1.09 (9.01-10.13)</td>
<td>10.20±0.89 (9.74-10.66)</td>
<td>0.63</td>
<td>6.58</td>
<td>0.65B</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

N, Newtons, cm, centimeters, Δ, mean absolute change; Δ%, mean percent change; ES, effect size; A small effect size; B moderate effect size; C large effect size.

Figure 3: Individual responsiveness to the NHE training program. Black lines indicate individual responses, and vertical grey bars show the group average values. Δ = absolute and percent changes of responders and non-responders.

The NHE training program implemented here increased both the eccentric knee flexor strength and the BF LH fascicle length. More than two-thirds of players demonstrated a meaningful increase in eccentric strength, while nearly half achieved consistent fascicle length increases with the NHE training.

Measures of eccentric knee flexor strength have been performed through isokinetic dynamometers for decades, and those devices are considered the gold standard tool for assessing human strength through joint torque measures. A few years ago, Opar et al.\(^{30}\) validated a prototype allowing a cheaper and faster assessment of the eccentric knee flexor strength during the NHE execution. While a large cohort study found no clinical value of strength tests with isokinetic dynamometry or the NHE device for predicting risk of hamstring injury,\(^{34}\) cohort studies with soccer,\(^{12,14-16}\) Australian football,\(^{19}\) rugby,\(^{18}\) and sprinters\(^{17}\) have demonstrated that athletes with eccentric knee flexor weakness are more susceptible to hamstring injury. For this reason, eccentric strength was selected as the primary outcome of the current study, and findings demonstrated that an 8-week NHE training program improved eccentric strength of the knee flexor muscles of female soccer players.

Professional male soccer players have demonstrated eccentric knee flexor strength values ranging from ~299 N to ~411 N during the NHE,\(^{34,35}\) while female players in the present study had ~258 N. Previous studies involving 6-10 weeks of NHE training have found increases of 7-11% on the eccentric knee flexor strength in well-conditioned male athletes.\(^{23,27,36,37}\) Therefore, the average increase of ~13% presented by female professional players in the current study suggest a satisfactory response to the NHE training program. It has been suggested that for every 10 N increase in eccentric knee flexor strength, the risk of hamstring injury can be reduced by 9% in male soccer players.\(^{12}\) Although the same numbers should not be assumed for female players, it is plausible to speculate that the approximate 35 N increase in eccentric strength found in our study may have aided the prevention of hamstring injury along the season.

A prospective cohort study found that soccer players with
shorter BF_{LH} fascicles were four times more likely to suffer a subsequent hamstring injury than those with longer fascicles.\textsuperscript{12} The mechanism by which shorter fascicles predispose athletes to injury is not entirely clear, but a reasonable hypothesis suggests that short fascicles (i.e., fewer in series sarcomeres) may be more susceptible to excessive stretching and subsequent injury during eccentric high-intensity contractions,\textsuperscript{38} such as those performed during high-speed running. The fascicle lengthening in response to the NHE training was expected in the present study because it has been consistently reported in both active subjects\textsuperscript{24} and well-conditioned athletes.\textsuperscript{23,27} However, it is curious that female players in the present study increased their BF_{LH} fascicle length (~7% or ~0.6 cm) with a slightly lower magnitude compared to male athletes submitted to the same training program periodization (~9-10% or ~1 cm).\textsuperscript{23,27} The individual responsiveness is an interesting analysis for professionals working in the medical departments and coaching staffs of team sports. Although the average values give us an idea of the team’s behavior, it is important to note that individual responses varied. In the present study, 71% of players had consistent muscle strength gains with the NHE training, which is a similar percentage of responders than those found in male soccer players engaged in a NHE training program during preseason (19 out of 25 players, 76%).\textsuperscript{31} Conversely, half of players engaged in the NHE training program in the current study did not experience fascicle length enhancement. All players were engaged in the same soccer training routine and all of them attended every NHE training session, thus adherence issues cannot explain the non-responders. Baseline status also does not seem to explain the training responses, as illustrated by the similar pre-training levels between responders and non-responders in Figure 3. Interestingly, all non-responders for the eccentric strength were also non-responders for the BF_{LH} fascicle length. Further investigation is needed to understand why some athletes respond to NHE training and others do not. In addition, it would be a sports medicine breakthrough if future studies could determine if responders and non-responders have different injury rates during the season.

Like all sport injuries, muscle strains are complex and multifactorial in nature,\textsuperscript{6} and most soccer players present multiple risk factors for sustaining a hamstring injury.\textsuperscript{28} According prospective data,\textsuperscript{12} eccentric knee flexor strength and BF_{LH} fascicle length account for approximately 30% of the risk associated with hamstring injury occurrence, thus the other 70% cannot be undervalued. The posterior chain flexibility,\textsuperscript{39} hamstring-to-quadriceps strength ratios,\textsuperscript{14,16} and proximal neuromuscular control\textsuperscript{40} are examples of modifiable factors also associated with hamstring injury. Therefore, despite the present study focused the effects of a single exercise on only two of those risk factors (eccentric knee flexor strength and BF_{LH} fascicle length), a comprehensive approach is recommended for preventive programs.\textsuperscript{41} The current study has limitations. First, this is not a randomized controlled trial. It means that the NHE cannot be assumed as the single factor responsible for changes observed on muscle strength and architecture, despite previous evidence in male players has demonstrated that regular soccer training does not affect the outcomes assessed here.\textsuperscript{25,36} Second, it was not possible to follow the injury rates of the professional players along the subsequent season, which would allow us to verify whether the individual responsiveness to the NHE training program had an influence on the hamstring injuries or not. Third, the number of participants in the current study is small, and caution is recommended regarding the percent distribution of responders and non-responders to the NHE training program. Despite these limitations, this study presents high ecological validity because it was done within the real-world of competitive soccer.

CONCLUSION

The results of this study indicate that an 8-week NHE training program performed twice a week during preseason increases the eccentric knee flexor strength and the BF_{LH} fascicle length in professional female soccer players. The positive effects on two injury risk factors for hamstring strain injury support the adoption of the NHE within a prevention program. Medical and coaching staffs must be attentive and monitor individual responses because not all players benefit from the NHE intervention.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

ACKNOWLEDGEMENTS

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REFERENCES


A Preseason Training Program With the Nordic Hamstring Exercise Increases Eccentric Knee Flexor Strength and Fascicle...


The Relationship Between Hip Range of Motion and Pitching Kinematics Related to Increased Elbow Valgus Loads in Collegiate Baseball Pitchers: A Pilot Study

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University of Florida Health

Keywords: pitching mechanics, hip range of motion, elbow valgus, baseball

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Background
Hip range of motion (ROM) during baseball pitching is associated with trunk rotation and shoulder kinematics, which has shown to influence medial elbow valgus loading and pitching performance. The purpose of this study was to measure the relationship between hip rotational ROM and kinematic variables that influence elbow valgus loads in Division 1 collegiate pitchers.

Study Design
Descriptive laboratory study.

Methods
Three-dimensional pitching motion (Motion Analysis Corp, Santa Rosa, California) analyses were captured for seven Division 1 baseball pitchers. Six kinematic measurements related to medial elbow valgus loading were calculated while the pitchers threw fastballs. Inclinometer measurements were used to measure hip internal (IR), external (ER) ROM, and total rotational arc at the hip (IR + ER ROM). Correlations were used to evaluate the association between hip IR, ER, and total rotational arc ROM (TRARC) and six kinematic variables.

Results
Trunk angular velocity was correlated to trail hip ER and TRARC (p < 0.01). Lead hip total arc ROM was associated with maximum shoulder ER (p < 0.01). Lead hip IR was correlated to elbow flexion angle at ball release (p < 0.01).

Conclusion
Hip ROM during pitching is associated with trunk angular velocity, maximum shoulder ER and elbow flexion angle at ball release. Alterations in hip TRARC appears to influence trunk rotation velocity leading to dependence on increased shoulder ROM and decreased elbow flexion angle at ball release which is associated with diminished pitching performance and excessive medial elbow valgus loads.

Level of Evidence
level 3

INTRODUCTION
Increased valgus loads at the elbow joint while pitching has been shown to lead to medial elbow instability, chondral degradation at the radial head and capitellum as well as at the olecranon, and ulnar collateral ligament injury.1–8 The increased valgus loading produces tensile stresses along the medial elbow as well as compressive and shear forces along the lateral and posterior elbow.5,8–11 This development is a result of the inability of the elbow to produce sufficient
varus torque to balance the accumulating valgus torque created by increasing valgus loads.\textsuperscript{6–11} Elbow valgus loading is at the most extreme when the pitching shoulder is in maximum external rotation during the late cocking and early portion of the acceleration phase.\textsuperscript{3,8–11}

The accumulation of valgus loads can subjugate the ulnar collateral ligament (UCL) to injury either through a sudden rupture or prolonged repetitive stress.\textsuperscript{5,12} Specifically, pitchers are highly vulnerable to increased valgus loading and are at a higher risk to develop medial elbow pathology and undergo a UCL reconstruction 5.9 times greater than their non-pitching counterparts.\textsuperscript{13} Epidemiological studies demonstrated that the average rate of UCL surgeries performed in Division 1 baseball following the 2017 season occurred at rate of 0.86 surgeries per collegiate program with 85.8% of those surgical cases being pitchers.\textsuperscript{13} Additionally, the increased valgus loading will also increase the stress along the cartilaginous structures of the capitellum and the posterior-medial aspect of the olecranon leading to lateral compartment chondrosis and posterior-medial impingement during the deceleration phase.\textsuperscript{8,11}

Aguinaldo et al.,\textsuperscript{7} found that kinematic variables such as early trunk rotation, increased shoulder external rotation (ER), and decreased elbow flexion have been shown to increase valgus loads at the medial elbow.\textsuperscript{7} Additionally, Di Giovine et al.,\textsuperscript{14} demonstrated that increased shoulder abduction during the late cocking phase resulted in increased valgus loading at the medial elbow.\textsuperscript{14} Furthermore, Werner et al.,\textsuperscript{15} looked at 37 kinematic and kinetic variables and found that pitchers with increased shoulder horizontal abduction angular velocity and shoulder abduction angle at lead foot contact, elbow angle at peak valgus stress and peak shoulder external rotation torque had increased elbow valgus loading during the late cocking phase.\textsuperscript{15} In addition to these established kinematic predictors of elbow valgus loading, lower extremity range of motion (ROM) also contributes to the kinetic chain of the pitching motion.\textsuperscript{16–18}

Specifically, restrictions in hip rotational ROM can influence performance and increase risk for medial elbow pathology.\textsuperscript{7,16,19,20} Restricted lead and trail hip ROM can affect the pitcher’s shoulder positioning.\textsuperscript{21,22} Decreased hip ROM causes the pitching arm to be out in front of the pitcher’s body forcing the pitcher to throw across their body.\textsuperscript{22,23} This scenario theoretically leads to a dampening of the transfer of energy from the lower extremities. The results lead to a potential reliance on the upper extremities to produce force needed to achieve ball velocity, leading to increased medial elbow valgus torque.\textsuperscript{21,22} Too much hip motion and the pitching arm will lag behind the already rotated trunk.\textsuperscript{22,23} In this scenario, the overhead athlete will compensate for early trunk rotation by increasing shoulder ER ROM. Increased shoulder ER ROM has been associated with increased valgus loads at the medial elbow.\textsuperscript{7,21,22}

Given the interaction between hip motion and pitching mechanics, a salient link may exist between restrictions in hip rotational ROM and medial elbow dysfunction. Thus, the purpose of this exploratory study was to measure the relationship between hip rotational ROM and kinematic variables that influence elbow valgus loads in Division 1 collegiate pitchers. Determining if a relationship exists between hip ROM and valgus forces at the elbow may aid in developing interventions to address poor pitching mechanics, while improving pitching performance.

**MATERIALS AND METHODS**

**PARTICIPANTS**

A total of seven Division 1 collegiate baseball pitchers (mean age, 19.57 ± 1.1 years; mean height, 1.89 ± .06 m; mean weight, 93.3 ± 6.8 kg) consented to participate in this study. (Table 1) Five subjects were right-handed dominant and two subjects were left-handed dominant. All subjects were healthy at the time of testing, currently active, reported no trunk, upper or lower extremity injury in the past six months or had history of upper or lower extremity surgery. Prior to participation, all subjects signed a written informed consent approved by the University of Florida Health Science Center Institutional Review Board (IRB-01).

**PROCEDURES**

All subjects were tested prior to the beginning of preseason workouts. All hip rotational ROM measures were performed by the same two American Physical Therapy Association (APTA) board sports certified specialist physical therapists. One to stabilize and one to record measurements. Hip ROM testing occurred prior to kinematic testing at the University of Florida Human Dynamics Laboratory.

**HIP ROTATIONAL ROM MEASUREMENTS**

Hip ER and internal rotation (IR) ROM measurements were taken with a bubble inclinometer while the subject was placed in a prone position with hip of interest in 0 degrees of extension and abduction with knee in 90 degrees of flexion.\textsuperscript{24,25} A two-examiner method was utilized. One examiner placed one hand on the testing hip greater trochanter

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total Sample (N = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years) Mean ± SD</td>
<td>19.6 ± 1.1</td>
</tr>
<tr>
<td>Height (meters) Mean ± SD</td>
<td>1.89 ± 0.06</td>
</tr>
<tr>
<td>Weight (Kilograms) Mean ± SD</td>
<td>93.3 ± 6.8</td>
</tr>
<tr>
<td>Throwing Hand Dominance</td>
<td></td>
</tr>
<tr>
<td>Right handed = 5</td>
<td></td>
</tr>
<tr>
<td>Left handed = 2</td>
<td></td>
</tr>
<tr>
<td>College Playing Year</td>
<td></td>
</tr>
<tr>
<td>Junior = 2</td>
<td></td>
</tr>
<tr>
<td>Sophomore = 3</td>
<td></td>
</tr>
<tr>
<td>Freshman = 2</td>
<td></td>
</tr>
<tr>
<td>Ball velocity (miles per hour)</td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>93.2 ± 3.1</td>
</tr>
</tbody>
</table>

*Standard Deviation
Table 2: Hip Range of Motion and Kinematic Variables Measurements for Collegiate D1 Baseball Pitchers

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trail Hip ER ROM (degrees)</td>
<td>34.3 ± 7.5°</td>
</tr>
<tr>
<td>Lead Hip ER ROM (degrees)</td>
<td>29.4 ± 8.9°</td>
</tr>
<tr>
<td>Trail Hip IR ROM (degrees)</td>
<td>12.6 ± 3.6°</td>
</tr>
<tr>
<td>Lead Hip IR ROM (degrees)</td>
<td>16.9 ± 8.5°</td>
</tr>
<tr>
<td>Trail Hip TRARC (degrees)</td>
<td>46.9 ± 5.6°</td>
</tr>
<tr>
<td>Lead Hip TRARC (degrees)</td>
<td>46.3 ± 11.5°</td>
</tr>
<tr>
<td>Maximum Shoulder External Rotation (degree)</td>
<td>171.6 ± 8.4°</td>
</tr>
<tr>
<td>Shoulder Abduction Angle at Foot Contact (degree)</td>
<td>91.6 ± 9.5°</td>
</tr>
<tr>
<td>Elbow Flexion Angle at Ball Release (degree)</td>
<td>21.87 ± 5.5°</td>
</tr>
<tr>
<td>Maximum Shoulder Horizontal Adduction Angular Velocity (degree/second)</td>
<td>1315.7 ± 257.4%/s</td>
</tr>
<tr>
<td>Onset of Maximum Trunk Angular Velocity (% of Pitching Cycle)</td>
<td>95 ± 6.2%</td>
</tr>
<tr>
<td>Onset of Maximum Elbow Flexion (% of Pitching Cycle)</td>
<td>105.9 ± 1.9%</td>
</tr>
</tbody>
</table>

ER= External rotation, ROM= range of motion, IR= Internal rotation, TRARC= total rotational arc range of motion

and pelvis to minimize excess movement and used the other hand to grip the subject lower leg to passively move the hip until first resistance was detected. The second examiner placed the bubble inclinometer proximal to the medial malleolus aligned with the shaft of the tibia to record ER and IR ROM. Total hip rotational ROM was calculated as the sum of hip ER and IR ROM. This measuring method has shown good interclass correlation (ICC = .98).24

PITCH BIOMECHANICS PREPARATION

Motion capture set-up was based on previously validated methods.26,27 Motion analysis was captured with a high-speed, 12-camera optical motion capture system (Motion Analysis Corp, Santa Rosa, California). Data were captured at 200 Hz. Fifteen reflective markers were applied bilaterally at the lateral tip of the acromion, lateral humeral epicondyle, greater trochanter, lateral femoral epicondyle, lateral malleolus, and hallux; additional markers were placed on the radial and ulnar styloid processes of the dominant hand with one marker placed on the non-dominant radioulnar joint.26,28 Reflective tape was placed on a standard NCAA collegiate ball.

Each player was instructed warm-up based on their standard team regulated stretching and throwing preparation routine. The players received standardized instructions to pitch ten game-effort pitches from the wind-up position off an indoor mound (with a standard slope of one inch in height for every foot nearer to home plate); all pitches were 2-seam fastballs. Each player pitched into a marked area along a wall net that was the same size as home plate (43.18 cm X 43.18 cm). Data was collected from the three pitches with the greatest accuracy and velocity. Ball velocity was measured with a radar gun.

The pitching cycle (lead foot contact to ball release) was normalized to 100%.26,29 The variables calculated included: 1) three joint angles (maximum shoulder ER during the pitching cycle, shoulder abduction angle at foot contact, and elbow flexion angle at ball release); 2) one angular velocity (maximum shoulder horizontal adduction angular velocity); and 3) two variables (initiation of maximum trunk angular velocity and initiation of maximum elbow flexion). These variables were calculated as the percentage of the pitching cycle at which the event occurred. These variables were chosen based on their influence on elbow valgus loading during the cocking and acceleration phase.7,14,15,22,30

STATISTICAL ANALYSIS

All statistical analyses were performed with SPSS (version 22.0; IBM Corp., Chicago, IL, USA). Descriptive statistics (mean and standard deviation) were calculated for Hip ROM and kinematic variable measurements. (Table 2) Pearson’s product correlations were used to evaluate the association between lead and trail hip IR, ER, and total rotational ROM and the six kinematic variables. Correlations were deemed significant if p was less than 0.01.

RESULTS

The correlations between Hip ROM and biomechanical variables are shown in Table 3.

RELATIONSHIP BETWEEN TRAIL HIP ROM AND BIOMECHANICAL VARIABLES

The trail hip TRARC was significantly related to the onset of trunk angular velocity (r = .712, p = .003). There was also a significant correlation between trail hip ER and the initiation of trunk angular velocity (r = .650, p = .009). (Figures 1A and 1B)
Table 3: The Relationship Between Hip Range of Motion and Biomechanical Variables for Collegiate D1 Baseball Pitchers

<table>
<thead>
<tr>
<th>Kinematic Variables</th>
<th>Trail Leg</th>
<th>Lead Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Arc of Motion</td>
<td>External Rotation</td>
</tr>
<tr>
<td>Maximum Shoulder External Rotation</td>
<td>R=0.460 (p=0.058)</td>
<td>R=0.350 (p=0.123)</td>
</tr>
<tr>
<td>Shoulder Abduction Angle at Foot Contact</td>
<td>R=0.096 (p=0.441)</td>
<td>R=0.040 (p=0.655)</td>
</tr>
<tr>
<td>Elbow Flexion Angle at Ball Release</td>
<td>R=0.240 (p=0.604)</td>
<td>R=0.326 (p=0.475)</td>
</tr>
<tr>
<td>Maximum Shoulder Horizontal Adduction Angular Velocity</td>
<td>R=0.009 (p=0.832)</td>
<td>R=0.002 (p=0.931)</td>
</tr>
<tr>
<td>Onset of Maximum Trunk Angular Velocity</td>
<td>R=0.712 (p=0.003)*</td>
<td>R=0.650 (p=0.009)*</td>
</tr>
<tr>
<td>Onset of Maximum Elbow Flexion</td>
<td>R=0.129 (p=0.403)</td>
<td>R=0.051 (p=0.612)</td>
</tr>
</tbody>
</table>

* Statistically significant correlation (p < .01)

RELATIONSHIP BETWEEN LEAD HIP ROM AND BIOMECHANICAL VARIABLES

The lead hip total arc of motion was significantly related to maximum shoulder ER (r = 0.695, p = .005). (Figure 1C) There was a significant correlation between elbow flexion angle at ball release and lead hip IR (r = .952, p = .001). (Figure 1D)

DISCUSSION

The influence of hip ROM is vital to developing obligatory trunk and upper extremity torque and ball velocity during the pitching motion.\(^{19–21,31,32}\) Most collegiate pitchers will either generate power through their stance leg in a load and drive strategy or by converting the force generated by their body moving towards their intended target into ball velocity by rotating around their stride leg.\(^{8,19,31,32}\) A decrease in hip ROM may initiate a series of compensatory actions within the pitching motion which may lead to increased elbow valgus torque and loading.\(^{2,7,10,14,16,19,22,32}\) The current findings suggest that there may be an association between hip ROM and established kinematic influencers of increased elbow valgus torque during the pitching motion.\(^{2,7,10,14,16,19,22,32}\)

Lee et al.\(^{33}\) described the hip as being the principle structure initiating the spine to rotate.\(^{35}\) From a kinematic perspective, the trail hip will initiate pelvic rotation which will be followed by trunk rotation which will influence lead foot contact position and overall pelvic orientation. If there is too much hip rotation, then the lead foot and pelvis will be in a more open position.\(^{21–23,34}\) Conversely, if there were too little hip rotation, the lead foot and pelvis would be in a more closed position.\(^{21–23,34}\) Fortenbaugh et al.\(^{35}\) described that improper timing of pelvic rotation and trunk rotation would decrease pitching performance and increase stresses on the anterior shoulder and medial elbow.\(^{35}\) The authors reported that pelvic rotation should occur between 28% and 35% of the pitching cycle while trunk rotation should occur between 47% and 53% of the pitching cycle.\(^{35}\)
The current findings demonstrated a correlation between trail hip total arc of motion and trunk angular velocity, which may provide further support showing that hip rotational ROM is correlated to pelvic orientation and trunk rotation and velocity. Additionally, decreased trail hip ER will restrict the forward movement of the pitcher’s trunk over the lead leg dampening the transfer of energy from the lower extremities leading to increased shoulder ER. However, the current findings did not demonstrate a correlation between lead hip rotational ROM and trunk angular velocity. We believe that our findings were due to our small sample size and although the results did not reach statistical significance, they did demonstrate that pitchers who rotated their trunks earlier in the pitching cycle appeared to have increased lead hip total arc of motion.

The current findings demonstrate that there is an association between lead hip total arc of rotational motion and maximal shoulder ER. This finding is consistent with previously reported findings showing that diminished as well as excessive lead hip rotational ROM can influence throwing shoulder ER during the late cocking and early acceleration phase. For example, inadequate lead hip ROM can cause a domino effect leading to decreased stride length and damped lower extremity force production. The pitcher will be forced to throw across his body to compensate for the lack of force production by increasing shoulder ER to generate ball velocity. As a result, the pitcher may rely on shoulder rotation as the primary force generator while pitching. This method of force generation relies on increasing shoulder ER to rapidly move into IR to generate ball velocity, which has been shown to increase shoulder ER and elbow valgus torque, which may not only have a detrimental effect on pitching performance, but may lead to medial elbow pathology. Increased lead hip ROM will lead to the opposite effect, where the pitching shoulder lags behind the early rotating trunk. In this scenario, the pitcher will also have to compensate for reduced ball velocity by increasing shoulder ER. In this instance however, due early pelvic rotation, the pitcher has to compensate by speeding up the pitching arm to compensate for the de-rotated trunk. Again, due to early trunk rotation, the shoulder rapidly rotating from ER to IR would generate ball velocity. In both instances, shoulder ER is increased which may lead to increased medial elbow tensile stresses.

The current data also showed that lead hip IR correlated to elbow flexion angle at ball release. Aguiñaldo et al., demonstrated that a decrease in elbow flexion angle was linked to an increase in elbow valgus torque. The authors surmised that this occurred because increased elbow flexion would reduce the lever arm (throwing arm) around the trunk as the pitcher moves toward the intended target. The shorter lever arm would lead to decreased elbow valgus torques compared to a more extended elbow, which would act as a longer lever. A more extended elbow during the pitching motion may be indicative of a throwing shoulder that lags behind a rotating trunk. This shoulder lag can be linked to excessive lead hip IR. However, the findings of the current study demonstrated an average lead hip IR of 16.9 degrees, which is a smaller angle that previous research has shown to be ideal for pitchers. Such findings would suggest restricted lead hip IR in this cohort. Sekiguchi et al. found that decreased lead hip IR was significantly associated with an increased risk for shoulder and elbow pathology in a 9-12 year pitching cohort. Although younger than the current cohort, the authors believe that a similar situation may occur in the studied population, where decreased lead hip IR would lead to early pelvic rotation speeding up ball delivery and therefore altering the timing of elbow flexion at foot contact and may increase valgus loading along the elbow.

The current findings did not demonstrate a correlation between lead and trail hip ROM and maximum shoulder horizontal adduction angular velocity and shoulder abduction angle at foot contact. Previous published research has demonstrated that pitchers with excessive horizontal adduction during late cocking in a situation where the pitcher leads with his elbow will increase medial elbow stress due increased varus elbow torque. In addition Matsuo et al. showed that at late cocking pitchers with an angle less than 90-100 degrees of abduction during foot contact would demonstrate increased elbow varus torque. Both scenarios, a pitcher leading with his elbow and or with decreased shoulder abduction would increase deleterious stresses along their medial elbow and diminished ball velocity.

The results can be used to gain preliminary insight to the relationship between hip ROM and pitching kinematics related to elbow valgus loading. Although it may be difficult
to address and measure pitching kinematics or kinetics within the clinic, a thorough understanding of hip anatomy, pathomechanics, and muscle physiology can assist with making informed decisions regarding the genesis of injury when evaluating the pitcher. While, the current study was not powered to determine injury risk, there seems to be a relationship between hip ROM as a clinically modifiable factor and pitching kinematics related to elbow valgus loading. These findings suggest hip ROM should be examined as part of the overhead athlete assessment during the evaluation process.

This study has several limitations when interpreting the results. The sample size is limited in number and consisted of seven Division 1 baseball pitchers, which may have been too small to accurately assess relationships. However, collegiate pitching populations are historically small and accessibility to this population and measurements within a lab can be quite difficult to ascertain. Additionally, the results cannot be extrapolated to other age (youth) or level (professionals). Furthermore, intra-rater reliability was not assessed when measuring hip ROM in the prone position in this study. However, reliability has been previously reported for the hip ROM measurements positioning and technique that we incorporated. The authors utilized the same two clinical examiners in the same role, one to stabilize and one measure for every athlete. Kinematic variables were acquired in a laboratory using an artificial mound, which is not identical to pitching on the field.

CONCLUSION

In conclusion, previous literature has described the relationship between specific kinematic and kinetic variables and medial elbow valgus loading. The findings of the current study elucidate the relationship between hip ROM and specific kinematic predictors of medial elbow valgus loading; i.e. initiation of trunk rotation, increased maximum ER, and increased elbow flexion angle at ball release. Understanding the relationship between hip ROM and pitching kinematics related to increased medial elbow valgus loading is instrumental for healthcare and performance providers to understand how alterations hip ROM may affect the pitching motion and consequentially pre-dispose the pitcher to injury and decreased performance. Additionally, hip ROM should be screened by practitioners when determining prevention and rehabilitation programs for collegiate pitchers.

DISCLOSURES

This study was approved by the University of Florida Health Science Center Institutional Review Board (IRB-01). The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article.

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Line Hops and Side Hold Rotation Tests Load Both Anterior and Posterior Shoulder: A Biomechanical Study

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Keywords: shoulder, movement system, moments, kinetics, functional testing, forces, electromyography

https://doi.org/10.26603/001c.21454

Background
Clinical tests should replicate the stressful positions encountered during sport participation. Evaluating the kinetic and electromyographical demands of clinical tests enables clinicians to choose appropriate tests for specific sports.

Purpose
To describe the shoulder forces and muscle activation levels during closed chain functional tests of Line Hops (LH) and Side Hold Rotation (SHR).

Study Design
Descriptive biomechanical study

Methods
Ten asymptomatic participants were examined in a university laboratory. Two functional tests were evaluated using three-dimensional video analysis and electromyography to measure shoulder forces, moments, and muscular activity levels.

Results
SHR produced a peak average posterior translation force of 4.84 N/kg (CI 95 4.32–5.36N/kg) and a peak average anterior translational force of 1.57 N/kg (CI 95 1.10–2.01N/kg). High levels of serratus anterior (98% maximum voluntary isometric contraction (MVIC)) and infraspinatus (52% MVIC) were recorded during SHR. LH produced a posterior translational force of 4.25 N/kg (CI 95 3.44–5.06N/kg). High levels of serratus anterior (105% MVIC) and infraspinatus (87% MVIC) were recorded during the push off phase of this activity.

Conclusions
LH and SHR placed large posterior translational forces that approached half of a person’s bodyweight on shoulder structures. SHR produced an anterior translation force at extremes of horizontal abduction placing approximately 18% of bodyweight on shoulder structures. The LH test required the serratus anterior to provide power to push the upper torso of the ground while both the serratus and the infraspinatus provides scapular and humeral stability, respectively.

Level of Evidence
4: Case series
INTRODUCTION

The incidence of shoulder injuries in contact and collision sports is high with potentially career-ending consequences. The shoulder is the most commonly injured peripheral region in rugby union, and high force collisions are commonplace. Common positions of shoulder injury in contact and collision sports are well documented. Reaching out to grab an opponent with the arm elevated, horizontally abducted, and externally rotated places stress on anterior shoulder structures and can result in an anterior shoulder dislocation. Falling on an outstretched arm with the arm extended out in front or blocking with arms fully extended in American football, produces an axial load through the humerus causing a posterior shear force and can result in a posterior shoulder dislocation if adequate force is applied. These collision sports apply a great deal of stress to the shoulder which is why regaining adequate stability is necessary before return to sport.

Following an injury, the goal of rehabilitation is to restore athletes’ function to previous levels and provide safe return to play. However, the high rates of recurrent shoulder injuries in rugby (75%) suggest that current rehabilitation strategies are sub-optimal. Rehabilitation consists of exercise prescription which incrementally increases stress and load to contractile and non-contractile tissues, in order for the tissues to adapt. Significant electromyographical (EMG) research exists that helps guide clinicians in exercise selection to ensure activation and strengthening of the necessary musculature. Additionally, knowledge of the forces and moments at the shoulder could help guide exercise selection and return to play. During the functional phases of rehabilitation, exercises are selected to gradually expose the athlete to greater joint loads and provocative positions that challenge joint stability. It is critical that the loads produced by these exercises are understood so they can be incorporated appropriately into rehabilitation and return to sport testing. Thus, ensuring the appropriate direction and magnitude of stress is applied to the joint.

Vertical ground reaction forces (VGRF) have been studied during upper extremity functional tests. However, VGRF does not specifically describe the forces at the shoulder. Biomechanical modelling using inverse dynamics allows the calculation of forces and moments in six degrees of freedom at a joint. Clinicians could use this information to choose functional performance tests that stress shoulder tissues at the appropriate level and direction. The (SHR) and (LH) tests are reliable upper extremity functional tests that replicate positions of anterior and posterior shoulder instability. However, it is not known what biomechanical forces, moments, and muscle activation levels are produced during these tests. Therefore, the purpose of this study is to describe the shoulder forces and muscle activation levels during closed chain functional tests of the SHR and LH tests. This study provides clinicians with specific information regarding the shoulder forces and muscle activation in key musculature around the shoulder during the SHR and LH tests to assist with return to play decision-making for a patient with shoulder instability.

METHODS

PARTICIPANTS

This clinical laboratory observational study recruited 10 asymptomatic participants (age 25±4 years, height 172±8cm, mass 71±13kg) between August and November 2017. All participants were right-handed, and instrumentation and testing were performed on the dominant shoulder. Participants were included if they were able to perform five full push-ups. Participants were excluded if they had a history of upper extremity injury or surgery within the prior two years. Prior to testing, the study was explained to the participants, and they had an opportunity to ask questions before signing a consent form approved by the University of Kentucky’s Institutional Review Board. Age, body mass (kg) and height (m) were recorded.

STUDY PROCEDURES

The LH and SHR functional tests (Figure 1) were performed in a biomechanical laboratory to measure electromyographical (EMG) shoulder muscle activity. Forty reflective markers were applied to bilateral upper extremities and trunk to record kinematic trunk, shoulder, elbow, and wrist motions in order to calculate shoulder forces and moments using inverse dynamics. This study describes the direction and amplitudes of shoulder forces during functional testing.

EMG ELECTRODES APPLICATION AND NORMALIZATION

Five bipolar 4-contact surface EMG sensors (Trigno, Delsys Inc. Natick, MA) with an inter-electrode distance of one cm were applied to the subjects’ dominant right anterior deltoid, and serratus anterior using standard procedures (Appendix). Three muscles (supraspinatus, infraspinatus, and subscapularis) were instrumented with two sterile intramuscular fine wire electrodes each. Bipolar fine wire electrodes were placed in the muscle belly with an inter-electrode distance of 1cm using a two separate needle sticks per muscle. All EMG electrodes, leads, and wireless transmitters were taped down using double-sided tape and paper tape to minimize movement artifact. Electrode placements and maximal voluntary isometric contractions (MVIC) test positions are detailed in Appendix. Five second MVIC contractions were performed three times for each test position. A 60 second rest was given between each maximal effort for muscle recovery. The order of muscle testing was randomized.

KINEMATIC MARKERS

Forty reflective markers were attached with double-sided tape to a set of standardized anatomical locations (bilaterally on the anterior superior iliac spine, sternal notch, xiphoid process, spine of the 7th cervical vertebrae (C7), spine of the 8th thoracic vertebrae (T8), left 12th rib over the kidney and bilaterally on the anterior and posterior humeral head, medial and lateral humeral epicondyle, radial and ulnar styloid process, and the head of the third metacarpal). Clusters of four markers were placed on bilateral forearms, and upper arms, and a cluster of three-markers placed on
Figure 1: Line Hops and Side Hold Rotations

the sacrum with elastic strapping (Figure 2). Static calibration was performed with arms abducted to 90° and elbows flexed to 90°, captured using the coordinate system defined in Figure 3.

FUNCTIONAL TESTS
Participants performed two functional tests, the LH and SHR tests (Figure 1) in random order. These tests have been described previously as part of the Shoulder Arm Return to Sport battery.17 The SHR test is performed by having the participants start in a side plank, weight bearing through an extended arm, with the shoulder in horizontal abduction. Participants then rotate their body into shoulder horizontal adduction and back. The LH test is single arm hop back and forth over a 2.5cm line in a kneeling position with hips extended. Each participant performed five repetitions of each test. Due to time variation for each repetition, data were time normalized with a 0-100% time window.

Each functional task was divided into phases to evaluate EMG and force data. The SHR test was divided into four phases: 0%, 50% and 100% occurring when right horizontal abduction/adduction shoulder velocity was zero, while 25% and 75% were halfway points between zero shoulder velocity. The participant started and ended in maximal horizontal abduction. The LH test was divided into three phases: Flight phase commenced when there was no load (<10N) on the force plate. Catch phase commenced when the force plate was loaded >10N. Push phase commenced halfway between the start of catch and the start of flight.

Figure 2: Marker placement for Vicon model.

DATA ANALYSIS
KINEMATIC AND KINETIC DATA ANALYSIS

The three-dimensional kinematics of the trunk and upper extremities were measured with twelve high speed infrared video based three-dimensional motion capture system (Vicon Inc., Oxford, United Kingdom) synchronized with Bertec force plates (Model 6090, Bertec Corp., Columbus,
Three-dimensional marker trajectories were collected at a sampling frequency of 200Hz and raw force data from the force plates were collected at a sampling frequency of 2000Hz. Nexus software (Vicon Inc., Oxford, United Kingdom) was used to record time synchronized marker trajectory, force plate, and EMG data. Raw marker trajectory data were filtered using a low-pass Butterworth filter with a cut off frequency of 6Hz. Raw force and moment data from the force plates were filtered using a low-pass Butterworth filter with a cut-off frequency of 50Hz. Body segment (hand, forearm, humerus, and torso) inertial parameters were estimated using regression equations described by Dumas et al. Body mass (kg) and height (m) for each subject individually were taken into all 3D calculations to account for individual differences. Distal to proximal joint forces and moments were calculated via inverse dynamics using Visual 3D (v6 professional, C-motion INC., Germantown, MD, USA). All force and moment data were calculated as external to represent the net forces or moments acting on the shoulder during the tasks. Shoulder force and moment directions were reported relative to the thorax coordinate system (X: Right, Y: Posterior, Z: Inferior, Figure 3).

Through the entire movement, shoulder moments and forces were captured. The joint coordinate data relevant to mechanisms of anterior and posterior shoulder instability were selected. These included anterior/posterior, compression/distraction, and vertical ground reaction forces, and horizontal abduction/adduction moments. The kinetic data were ensemble averaged across participants.

**EMG DATA ANALYSIS**

All surface EMG data were collected at 1000Hz and 200 Hz for indwelling electrodes. A notch filter was applied between 50-60Hz prior to the data being smoothed using a root mean square function with a 50 millisecond time window. During performance of all testing, the same processing was applied and all EMG data were represented as a percentage of maximal voluntary isometric contraction (MVIC). The average of the three highest 250ms during the five second muscle test represented 100% MVIC for each muscle. The average EMG amplitude for each muscle was calculated across each of the phases, during the performance of both functional tests. The ensemble average was calculated from each participant to represent the EMG amplitude for each muscle by phase.

**STATISTICAL ANALYSIS**

The ensemble average for kinetic data were calculated for anterior/posterior forces, compression/distraction forces, and horizontal abduction/adduction moments. The maximum values and their respective 95% confidence intervals were reported. Maximal vertical ground reaction forces were calculated for each test. The ensemble EMG data are presented as descriptive data using median and interquartile ranges due to small sample size.

**RESULTS**

**SIDE HOLD ROTATIONS**

Maximum external posterior force was seen during the middle phase of the SHR test (4.84 N/kg, CI95 4.32-5.36N/kg). The maximal external anterior force was at the point of maximal horizontal abduction (1.57 N/kg, CI95 1.10-2.01N/kg). The maximal external compressive force (5.09 N/kg, CI95 4.45-5.61 N/kg) was at the beginning of the test movement. The SHR test also produced a horizontal abduction moment (0.36 Nm/kg, CI95 0.27-0.43 Nm/kg) at the beginning/end of the test movement (Figure 4). The maximum vertical ground reaction force (VGRF) was 415.26 N (CI95 366.59-463.93N) occurring at the beginning of the test movement (Figure 4).

The highest levels of serratus anterior occurred in the middle phases of the SHR test, during phases 25-50 (98 %MVIC) and 50-75 (73 %MVIC). Similarly, high levels of infraspinatus were seen during phases 25-50 (52 %MVIC) and 50-75 (45 %MVIC). High levels of these muscles occurred when the maximal posterior forces and horizontal abduction moments were recorded. Subscapularis (37 %MVIC) and supraspinatus (41 %MVIC) appeared most active at the end (75-100 %MVIC) of the SHR test when anterior translational forces and horizontal abduction moments were high. Anterior deltoid (71 %MVIC) appeared most active at the beginning of the movement as the participant moved into horizontal adduction (Figure 5).

**LINE HOP TEST**

The LH Test produced considerable posterior force during catch and push phase with maximal force (4.25 N/kg, CI95 3.44-5.06N/kg) occurring simultaneously with maximal VGRF (374.24 N, CI95 323.74-424.74 N) (Figure 6). There were maximal compressive forces (1.26 N/kg, CI95 0.87-1.65 N/kg) and maximal horizontal abduction moments (0.09 Nm/kg, CI95 0.02-0.16Nm/kg).

The highest levels of serratus anterior (105 %MVIC) and...
infraspinatus (87 %MVIC) activity occurred during the push phase of the LH test as participants pushed themselves away from the force plate (Figure 7). The anterior deltoid appeared most active during the push phase (52 %MVIC). Supraspinatus and subscapularis demonstrated relatively constant activity throughout the phases of the LH test (Figure 7).

DISCUSSION

This is the first study to calculate shoulder forces and moments using inverse dynamics during functional shoulder testing to better understand what stresses are applied to the shoulder. The goal of functional testing is to evaluate an athlete’s readiness to return to sport. The demands of contact sport are not well elucidated in the literature making direct comparisons impractical. The goal of this research was to provide clinicians with an appreciation of the demands occurring during two functional tests in order to match potential sport demands with functional tests. Incorporation of EMG data facilitates clinicians’ understanding of the muscles that are challenged during testing and what muscles may need additional strengthening if the subject fails testing. Both functional tests are single-arm closed chain tests that generated high loads as individuals must control a portion of their body weight. Both tests allow side-to-side comparisons.

The SHR test was designed to stress both anterior and posterior shoulder structures which are supported by the results. The peak anterior translation forces, horizontal abduction moments, and compression forces occurred at the beginning (0%) and ending (100%) portion of the test which was at the time of maximal horizontal abduction. This test is performed continuously, therefore these positions are the same. The highest levels of anterior deltoid, supraspinatus and subscapularis occurred during the phase 0-25% when horizontal adduction was initiated, and in 75-100% during deceleration of horizontal abduction. It appears these muscles are critical in both phases to control humeral position. These findings also agree with previous findings that the activity of the rotator cuff was specific to the direction of load. Cadaveric research has demonstrated that between 211-619N is necessary to anteriorly dislocate a shoulder. Comparison of the current study’s findings to these results required conversion of peak anterior translation force of 1.57 N/kg to 127N using the average body weight of the participants (71 kg = 696N). The anterior force (18%BW) is clearly below the threshold to cause dislocation, but the position of horizontal abduction is potentially provocative and would help clinicians identify if a patient has developed sufficient muscular stability and coordination to control these anterior translational forces.

The SHR test generated high posterior translational forces and horizontal adduction moments in the mid-point of the test when the weight bearing arm is in maximal shoulder horizontal adduction (Figure 1). Due to body-weight loads, reduced compression forces at the shoulder, and horizontal adduction position, the posterior translational forces were three times higher than anterior translational forces. The greatest activation in this horizontal adduction position was observed in the serratus anterior and infraspinatus. The serratus anterior was active to support the individual’s bodyweight, which is consistent with previous pushing literature. The high muscle activity in this position is reasonable due to the single-arm push-up posi-
tion of the patient, at this phase of the test. The increased infraspinatus activity was in response to external forces driving the humeral head posteriorly and reduced compression forces in the glenohumeral joint.

The LH test is a more dynamic test, requiring generation and absorption of landing forces as the individual pushes themselves over a line and back from their knees.\textsuperscript{17} The external force during this test is primarily directed in a posterior direction (Figure 6). The peak magnitude of both tests in a posterior direction were similar, even though the LH test (4.25 N/Kg = 301kg) was performed from a kneeling position while the SHR test (4.84N/Kg =343 Kg) was performed in a full push up position. Converting these normalized values to a clinically relevant value of percent of bodyweight revealed that both tests require a person to handle 43-49% of their bodyweight through one shoulder. When observing the peak magnitudes, the SHR test is greater, yet the dynamic nature of the LH test makes this test more demanding and more sport specific. The LH test VGRF stayed relatively constant at 400N (Figure 4), while the LH test VGRF changed from 0-300N (Figure 6) at a steep rate of change, especially during the catch phase. The posterior shear force also dramatically increased during the catch phase, indicating rapid loading of the posterior structures of the shoulder. The explosive pushing and catching of the LH test resulted in greater rate of force development when compared with the SHR test. The VGRF created during the LH test approached previously documented VGRF levels during a simulated falling test (390N).\textsuperscript{30} Chiu and Robinovitch\textsuperscript{30} also positioned participants on their knees, where they fell forward to land on their right hand with their elbow straight, onto a force plate. Participants in that study fell a maximum of 5cm and the authors predicted that extrapolation to larger fall heights would not result in larger VGRF values. However, falling expectedly from knees to land on the hand, may not accurately represent the magnitude of the forces involved in falling unexpectedly from a standing position. The LH test may not reach the exact same demands during sport but challenges an individual’s ability to both generate and absorb forces through the shoulder in a similar direction as falling on an outstretched hand or blocking in American football.

The muscular recruitment of the serratus anterior during the LH test is comparable to the SHR test, with maximal activity recorded during the push phase of the test (105 %MVIC). This is consistent with previous studies describing high serratus anterior activity during a push up plus.\textsuperscript{28} Pushing the torso back-and-forth across a line one-handed, is more challenging than simply doing a push up plus motion. During high levels of shoulder posterior force in the LH test (Figure 6), there were high levels of infraspinatus muscle activity (Figure 7). Thus, the rotator cuff activity in the LH test also responded to load, in a direction-specific manner.\textsuperscript{23–25} It is proposed that infraspinatus stabilized the humeral head from translating posteriorly in response to the posterior translational force of the catch phase. Infraspinatus activity was greatest during the push phase while pushing approximately 40% of the individuals’ bodyweight off the ground. This increase was necessary to facilitate shoulder compressive forces to stabilize the glenohumeral joint.\textsuperscript{31,32} Clinical testing of the LH test involves completion of a maximum number of repetitions in one minute. The mean number of LH recorded in healthy college participants was 24,\textsuperscript{17} while elite and schoolboy rugby players achieved a mean score of 32 repetitions, and a maximum score of 66 repetitions.\textsuperscript{33} It is unknown the effect of multiple repetitions on the endurance capacity and fatigue of the muscle.
Figure 6: a) External anterior/posterior shoulder force, b) horizontal adduction/abduction moment, c) compression/distraction force and d) vertical ground reaction force during phases of LH.

Data represents the ensemble average of 10 subjects with error bars representing 95% confidence boundaries on the mean. Forces in the anterior/posterior axis, are represented by positive values indicating anterior force and negative values indicating posterior force. Moments in the Horizontal adduction/abduction axis are represented by positive values indicating horizontal adduction moment, and negative values indicating horizontal abduction moment. Forces in the compression/distraction axis are represented by positive values indicating compression forces and negative values indicating distraction forces.
Comparison of this study’s findings was difficult due to limited biomechanical studies during functional tests, but a few do exist.\textsuperscript{15,16} Direct comparisons of VGRF were problematic due to methodological differences but comparisons can be drawn if average bodyweights are assumed. The Athletic Shoulder (ASH) test generated the greatest VGRF when the participant placed their arm in full flexion while laying prone describe as the “I” component and generated 1.59N/kg using the average weight of their participants which was 95kg.\textsuperscript{16} The peak VGRF has also been measured during the Closed Kinetic Upper Extremity Stability Test, where values of 0.68 N/kg were reported.\textsuperscript{15} Converting the peak VGRF produced in the LH test and SHR test yielded 5.3N/kg and 5.8N/kg respectively, based on the average weight of 71kg. Knowing the specific loads generated by tests and muscular activation levels allows clinicians to develop a logical progression to progressively increase demands on the shoulder to prepare them to return to sport demands.

LIMITATIONS

One of the limitations of this study is the small number of healthy participants with a relatively narrow age band. Use of previously injured athletes would improve external validity and provide some clinical relevance, as these tests are designed for athletes who are returning to sport from an injury but may also increase variability. However, the primary goal was to describe the maximum forces, moments, and muscle activity produced in these tests that may have stressed anterior and posterior shoulder structures. Another limitation was that participants were not instructed on how to land during the Line Hop test. The amount of elbow flexion during landing attenuates forces at the shoulder\textsuperscript{30} allowing for greater data variability but represents typical catching variations. In the SHR test, the participant was instructed to rotate as far as possible in horizontal abduction. The lack of specific arcs of motion obtained during the SHR test may account for the variation observed in EMG, force, and moment data. Additionally, the data reported were averaged from five trials not a complete one-minute test, so how these measures change over one minute is currently unknown and may demonstrate changes in muscle activation and mechanics over time. Finally, inverse dynamics does not isolate a specific ligamentous or musculotendinous structure to which forces are applied so it is not possible to determine the loads on a specific structure. Further research is needed to stress anterior shoulder structures, examine muscular contributions over a one-minute period and determine how fatigue affects these results. Longitudinal studies are also required to determine the ability of these tests to predict injury.

CONCLUSIONS

The kinetic and EMG analyses of these two clinical tests enable clinicians to understand and therefore choose appropriate tests for their patient’s needs. The posterior forces in both the LH test and SHR test were similar and peak values were approximately half of the participants’ bodyweight, indicating high levels of stress on posterior structures. Anterior forces were greatest at end range of horizontal abduction of the SHR test, primarily stressing the anterior GHJ structures. The LH test is a more dynamic task as demonstrated by changes in rate of force development compared to the SHR test. The weight bearing nature of both tests activated the serratus anterior to near maximal level while the infraspinatus was most challenged when external posterior
translational forces were greatest. The forces and moments of these tests are higher than those reported in previous research and may simulate loads experienced in contact and collision sports. This biomechanical approach allows clinicians to examine specific information about these tests so they undertake assessments that will match the needs of their patient to return to sport or function.

CONFLICT OF INTEREST
All authors declare no conflicts of interest.

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REFERENCES


Original Research

Comparative Pitching Biomechanics Among Adolescent Baseball Athletes: Are There Fundamental Differences Between Pitchers and Non-pitchers?

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Keywords: baseball, adolescent, trunk rotation velocity, ground reaction force, pitch velocity

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Background
Approximately 25% of youth baseball players pitch, with most young athletes predominately playing multiple positions. While some youth baseball players may primarily pitch, other players may only pitch on occasion, potentially creating a pitching skill level discrepancy. Understanding potential kinematic and kinetic differences between pitching and non-pitching baseball players can inform injury risk reduction strategies for amateur athletes.

Purpose/Hypothesis
To analyze differences in pitching biomechanics for fastballs, breaking balls, and change-ups in adolescent youth baseball players that identify as pitchers and non-pitchers.

Study Design
Retrospective cross-sectional study

Methods
Baseball players were designated as pitchers or non-pitchers, who then threw fastballs (FB), breaking balls (BB), and change-ups (CH) during a biomechanical assessment. T-tests, Mann-Whitney U tests, and ANOVAs with Bonferroni correction, and effect sizes (ES) were performed.

Results
Sixty baseball players (pitchers = 40; non-pitchers = 20; Age: 15.0 (1.1); Left-handed: 15%; Height 1.77 (0.09) m; Weight: 70.0 (12.5) kg) threw 495 pitches (FB: 177, BB: 155, CH: 163) for analysis. Pitchers threw 2 m/s faster and produced greater trunk rotation velocity (ES: 0.71 (95% CI: 0.39, 1.30, p<0.0001) than non-pitchers. Furthermore, pitchers demonstrated greater ground reaction force for FB compared to CH (ES: 0.48 (95% CI: 0.01, 0.94), p<0.0001). No other biomechanical differences were observed between pitchers and non-pitchers or between pitch types.

Conclusion
Despite throwing at greater velocity for all pitch types, baseball players that identify primarily as pitchers had overall similar kinematics and kinetics in comparison to baseball players that primarily identify as non-pitchers. Self-identified pitching baseball athletes have improved force transfer strategies for ball propulsion, utilizing different force.
production and attenuation strategies across different pitch types when compared to non-pitchers. Coaches should consider that novice pitchers may potentially have dissimilar trunk and ground reaction strategies in comparison to primary pitchers when designing appropriate pitch loading and recovery strategies.

Level of Evidence
3

INTRODUCTION

Youth baseball injuries remain a significant public health concern.1–4 There are over 15.6 million baseball participants in the United States,5 with 3 million playing Little League6 and almost 500,000 participating at the high school level.7 Up to 50% of youth baseball pitchers report arm pain during pitching, with a 52% and 86% increased risk of pain among pitchers that throw a curveball or slider, respectively.8 Furthermore, approximately 25% of adolescent baseball players pitch,9 with the majority of young athletes predominately playing multiple positions.10 While some adolescent baseball players may primarily pitch, other players may only pitch on occasion, potentially creating a pitching skill level discrepancy.

Pitching a baseball is a series of complex, multifaceted movements that produce high forces throughout the entire kinetic chain.11 In order to handle these high forces, pitchers must attempt to minimize forces to the shoulder and elbow through proper pitching mechanics.11,12 For example, two pitchers may pitch at the same velocity, but the one pitcher may generate greater muscle and joint forces, producing decreased force directed towards ball propulsion.13,14 Decreasing pitching upper extremity forces has been associated with overall pitching skill, with less skilled pitchers potentially resulting in increased injury risk.15 On the other hand, highly skilled pitchers generate increased pitch force and velocity but are better protected from these potentially adverse effects due to more of these high forces directed to ball propulsion.11 Understanding how pitching kinematics and kinetics differ between baseball players that primarily pitch or only pitch on occasion can assist clinicians and coaches in determining injury risk reduction strategies across a broader range of adolescent baseball athletes.

Different pitch types and/or deliveries are an essential component of pitching success. The ability to produce similar pitching mechanics between different pitch types delays pitch type recognition by the hitter, improving chances of a successful pitch.16 While producing a similar pitching motion between pitch types is recommended,16 discrepancies in kinematics and kinetics have been observed at the youth level.16–18 Differences in fastball and curveball kinematics and kinetics have been observed at the wrist and hand; these differences are likely not clinically significant because of the limited wrist and hand injury prevalence in baseball.19–21 However, fastballs produce greater kinetic forces at the shoulder and elbow in comparison to breaking balls and change-ups,16–18 which can potentially alter injury risk.22 Further, differences in pitching forces have been observed for different pitch types between different skill levels, with higher skill levels producing greater force generation for ball propulsion compared to upper extremity forces.15

Currently, it is not understood if adolescent baseball players who identify as pitchers or non-pitchers demonstrate different pitching kinematics or kinetics. Given the increased risk and severity of injury among pitching athletes,8,10 understanding potential differences in pitching kinematics and kinetic strategies can inform clinicians and coaches on potential injury risk reduction strategies in non-pitchers who are asked to pitch in a game. Therefore, the purpose of this study was to analyze differences in pitching biomechanics for fastballs, breaking balls, and change-ups among adolescent baseball players that identify as pitchers and non-pitchers. The authors hypothesized that those identifying primarily as pitchers would produce different kinematics and kinetics in comparison to adolescent baseball players that identify as non-pitchers.

METHODS

STUDY DESIGN

Prior to verbal and written consent and participation, all participants and their parents or guardians were informed of the risk and benefits of study participation. This study was approved by the Wake Forest School of Medicine Institutional Review Board. Baseball players from regional high schools and baseball academies participated in a pitching evaluation at the Wake Forest Pitching Laboratory. Inclusion criteria consisted of adolescent baseball players from all competition levels and between the ages 12 and 18. Participants were able to participate in all standard training, practices, and competitions at initial testing, and they threw at least two different pitch types (fastball, breaking ball, or change-up) based on prior pitching experience. Data were excluded if participants reported pain during any testing, had undergone surgery in the past twelve months, or were not participating in baseball-related training, practices, or games at the time of evaluation. Baseball players were then designated, through consensus between participants, parents, and coaches as those that were primarily pitchers and those that identified as non-pitchers (primarily played other positions such as catcher or shortstop) and who may pitch only on occasion.

BIOMECHANICAL ANALYSIS

Kinematic three dimensional (3D) motion data were collected using the 40 reflective marker set required for PitchTrak (Motion Analysis Corporation; Santa Rosa, California) with a sixteen-camera motion analysis system (Motion Analysis Corporation; Santa Rosa, California). Motion data were collected at 250 Hz. Ground reaction forces (GRF) were collected with three multi-component force plates (AMTI; Watertown, Massachusetts) embedded in the Perfect Mound
Statistical analyses

Means (standard deviations (SD)) and medians (interquartile ranges (IQR)) were calculated for both descriptive statistics (i.e., age, height, and mass) and biomechanical (kinematic and kinetic) variables. Each pitch type (fastball, breaking ball, and change-up) was analyzed separately to compare those that identified as pitchers and non-pitchers. To reduce the chance of Type 1 error, a Bonferroni correction was performed, with an alpha of 0.0009 calculated. A series of analysis of variance (ANOVA) and Kruskal-Wallis tests were performed to investigate the variability in pitch kinematics and kinetics between pitchers and non-pitchers. To observe those that identified as pitchers and non-pitchers. If significant differences were observed between pitches, Tukey’s or Dunn’s post hoc analyses were performed for specific pitch types differences. If findings were statistically significant, Cohen’s d effect sizes (ES) with 95% confidence intervals (95% CIs) were calculated. Effect sizes were rated as small (d = 0.20-0.50), moderate (d = 0.50-0.80), and large (d > 0.80).26 All analyses were performed in R version 3.5.1 (R Core Team [2013], R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/).

Results

Data from a total of 60 adolescent baseball players (pitchers: n = 40; non-pitchers: n = 20) were analyzed (Table 1). There were no statistical differences in age (p = .479), height (p = .048), or weight (p = .903). A total of 495 pitches were thrown, with pitchers throwing 342 pitches and non-pitchers throwing 153 pitches. The overall average mean pitch velocity was 29.5 (3.3) m/s; the mean fastball pitching velocity was 31.9 (2.8) m/s; the mean breaking ball pitch velocity was 27.2 (2.7) m/s; and the mean change-up pitching velocity was 29.0 (2.4) m/s. There was a moderate difference in fastball pitch velocity in favor of pitchers (pitchers: 32.6 (2.6) m/s, non-pitchers: 30.6 (2.7) m/s; p < .0001,

Table 1: Participant characteristics

<table>
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<tr>
<th>Variable</th>
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<th>Non-Pitchers (n = 20)</th>
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<td>70.5 (10.8)</td>
<td>68.9 (15.7)</td>
</tr>
<tr>
<td>Number of Pitches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fastball</td>
<td>177 [36%]</td>
<td>116 [34%]</td>
<td>61 [40%]</td>
</tr>
<tr>
<td>Curveball</td>
<td>155 [31%]</td>
<td>110 [32%]</td>
<td>45 [29%]</td>
</tr>
<tr>
<td>Changeup</td>
<td>163 [33%]</td>
<td>116 [34%]</td>
<td>47 [31%]</td>
</tr>
</tbody>
</table>

Means and standard deviations are reported as mean (SD). [ ] indicates percentage of the total number of observations.

Kinematics and kinetics

(Porta-Pro Mounds Inc; Sauget, Illinois). One plate was positioned under the pitching rubber with the front edge six inches in front of the rubber. The other two plates were angled at 4.8° and covered the landing zone. Each plate was covered with artificial turf to match the rest of the mound. Force plate data were collected at 1000 Hz. Pitchers threw from the Perfect Mound and were allowed to wear their cleats. The mound was engineered to meet major league specifications. Ball velocity was recorded with a Trackman (Porta-Pro Mounds Inc; Germantown, Maryland). Pitching models were defined using the PitchTrak model and segment coordinate systems were defined according to International Society of Biomechanics recommendations.23,24 Kinematics and kinetics were calculated from the entire pitching cycle and analyzed throughout the cycle and at key time points (high knee, front foot contact, ball release, follow-through). For the upper body segments, a top-down (distal-to-proximal) inverse dynamics approach was used for calculations.25 Shoulder distraction force is the component along the long axis of the segment coordinate system. Elbow valgus torque is the moment about the anterior/posterior axis of the segment. Variables extracted from the pitching reports included kinematics (pitching velocity, peak pelvis rotation velocity, peak trunk rotation velocity, time of peak pelvic rotation velocity, time of peak trunk rotation velocity, trunk flexion, lateral trunk tilt, hip shoulder separation at front foot contact) and kinetics (maximum elbow valgus torque, maximum shoulder distraction force, and maximum GRF).

Data from a total of 60 adolescent baseball players (pitchers: n = 40; non-pitchers: n = 20) were analyzed (Table 1). There were no statistical differences in age (p = .479), height (p = .048), or weight (p = .903). A total of 495 pitches were thrown, with pitchers throwing 342 pitches and non-pitchers throwing 153 pitches. The overall average mean pitch velocity was 29.5 (3.3) m/s; the mean fastball pitching velocity was 31.9 (2.8) m/s; the mean breaking ball pitch velocity was 27.2 (2.7) m/s; and the mean change-up pitching velocity was 29.0 (2.4) m/s. There was a moderate difference in fastball pitch velocity in favor of pitchers (pitchers: 32.6 (2.6) m/s, non-pitchers: 30.6 (2.7) m/s; p < .0001,
d = 0.76 (95% CI: 0.44, 1.08); breaking ball pitch velocity (pitchers: 27.8 (2.4) m/s, non-pitchers: 25.9 (2.7) m/s; p < .0001, d = 0.76 (95% CI: 0.40, 1.12); and a large difference for change-up pitch velocity (pitchers: 29.6 (2.1) m/s, non-pitchers: 27.6 (2.5) m/s; p < .0001, d = 0.86 (95% CI: 0.53, 1.24).

There was a moderate effect in favor of pitchers for greater trunk rotation velocity for fastballs (pitchers: 1053 (87) deg/s, non-pitchers: 988 (103) deg/s; p < .0001, d = 0.71 (95% CI: 0.39, 1.30) and change-ups (pitchers: 999 (104) deg/s, non-pitchers: 923 (107) deg/s; p < .0001, d = 0.73 (0.38, 1.08). No other kinematic or kinetic variables were different for any pitches between pitchers and non-pitchers (Table 2).

Pitching velocity was faster in pitchers among all three different pitch types. Pitchers threw fastballs at greater velocity than breaking balls (p < .0001, d = 1.92 (95% CI: 1.76, 2.08)); change-ups faster than breaking balls (p < 0.0001, d = 0.89 (95% CI: 0.63, 1.15)); and fastballs faster than change-ups (p < .0001, d = 1.28 (95% CI: 0.86, 1.69)). Pitchers displayed moderately greater trunk rotation velocity for fastballs compared to breaking balls (p < .0001, d = 0.59 (95% CI: 0.46, 0.72)), as well as fastballs compared to change-ups (p < .0001, d = 0.57 (95% CI: 0.22, 0.92)). Pitchers had moderately greater GRF when pitching fastballs in comparison to change-ups (p < .0001, d = 0.48 (95% CI: 0.01, 0.94)). No other kinematic or kinetic variables were different between pitcher pitch types.

Non-pitchers threw fastballs faster than breaking balls (p < .0001, d = 1.74 (95% CI: 1.66, 1.96)) and fastballs faster than change-ups (p < .0001, d = 1.15 (95% CI: 1.00, 1.30)). There was no difference in pitch velocity between breaking balls and change-ups (p = .005). There were no other kinematic or kinetic differences between non-pitcher pitch types.

**DISCUSSION**

Prior to this study, pitching biomechanics between adolescent baseball players that identify as pitchers or non-pitchers was not well-understood; such information may help inform injury risk reduction and training strategies. Therefore, the purpose of this study was to 1) analyze pitching biomechanical differences for fastball, change-ups, and curveballs between youth baseball players that identify as pitchers and non-pitchers; and 2) analyze pitching biomechanical differences between fastballs, change-ups, and curveballs within youth baseball players that identify as pitcher or non-pitchers. For all pitch types, pitchers threw an average of 2 m/s faster than non-pitchers. Pitchers displayed greater trunk rotation velocity for fastballs and change-ups in comparison to non-pitchers. Pitchers demonstrated greater maximum GRF for fastballs in comparison to change-ups, while non-pitchers did not demonstrate differences for maximum GRF between pitch types. All other kinematic and kinetic variables were similar between pitchers and non-pitchers for all pitch types, potentially demonstrating that pitchers utilize different trunk kinematics and GRF strategies but similar arm kinetic and kinetics in comparison to non-pitchers.

Adolescent pitchers demonstrated increased trunk rotation velocity for fastballs and change-ups in comparison to non-pitchers; further, pitchers displayed greater trunk rotation velocity for fastballs compared to both breaking balls and change-ups, while non-pitchers had similar trunk rotation velocity between all three pitch types. In this study, fastballs were delivered at a faster velocity than change-ups for both pitchers and non-pitchers. However, the discrepancies in trunk rotation velocity between groups demonstrate that pitchers potentially utilize different force production strategies for different pitch velocities. These dissimilarities in trunk rotation velocity between fastballs and change-ups are similar to findings in a previous study using trunk-based triaxial global positioning monitoring systems in collegiate baseball pitchers.27 The trunk has been observed to produce up to 50% of kinetic energy during the pitching motion.28 Thus, faster trunk rotation velocity warrants greater force transfer through the upper extremity and increasing ball propulsion.29,30 Also, greater trunk rotation strategies can increase forces through the upper extremity,31 while ineffective timing between pelvis and trunk rotation can inhibit ball propulsion velocity.11,23,29

Baseball pitchers may use multiple strategies for force generation in comparison to non-pitchers between different pitch types. Non-pitchers may use one force strategy for all pitch types and reduce pitch velocity by absorbing increased forces through the upper extremity instead of using this force for ball propulsion. The results of this study support this fact as non-pitchers threw with 2 m/s (5 mph) less velocity but demonstrated no significant difference in shoulder or elbow kinetics. There were no other differences in kinematics or kinetics between adolescent pitchers and non-pitchers. Coaches need to consider the potential for increased upper extremity forces when pitching different pitch types while monitoring non-pitcher's loading strategies.

A positive linear relationship has been previously observed between pitching velocity and elbow valgus torque in youth pitchers.32,33 Pitching places high stress on the musculoskeletal system. Pitchers that produce more force toward ball propulsion instead of upper extremity joint forces are potentially reducing injury risk.11,15 Compared to adolescent baseball players that primarily identify as pitchers, players that identify as non-pitchers may potentially utilize similar upper extremity pitching mechanics that generate decreased velocity. Coaches can use this information when considering pitch count and loading progressions for non-pitchers. For example, baseball players that primarily play a fielding position with intermittent pitching should be given more recovery consideration than a primary pitcher for an equal number of pitches.
<table>
<thead>
<tr>
<th></th>
<th>Fastball Pitchers</th>
<th>Fastball Non-Pitchers</th>
<th>P-value/ES(CI)</th>
<th>Curveball Pitchers</th>
<th>Curveball Non-Pitchers</th>
<th>P-value/ES(CI)</th>
<th>Change-up Pitchers</th>
<th>Change-up Non-Pitchers</th>
<th>P-value/ES(CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis Rotation Velocity (deg/s)</td>
<td>670 (109)</td>
<td>657 (96)</td>
<td>.398</td>
<td>634 (100)</td>
<td>619 (105)</td>
<td>.424</td>
<td>624 (87)</td>
<td>599 (99)</td>
<td>.122</td>
</tr>
<tr>
<td>Trunk Rotation Velocity (deg/s)</td>
<td>1053 (87)</td>
<td>988 (103)</td>
<td>&lt;.0001*</td>
<td>1000 (93)</td>
<td>941 (125)</td>
<td>.005</td>
<td>999 (104)</td>
<td>923 (107)</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Time to peak pelvis rotation velocity (s)</td>
<td>810 (741-879)</td>
<td>784 (708-860)</td>
<td>.085</td>
<td>792 (706-878)</td>
<td>771 (684-860)</td>
<td>.545</td>
<td>813 (724-904)</td>
<td>780 (696-864)</td>
<td>.336</td>
</tr>
<tr>
<td>Time to peak trunk rotation velocity (s)</td>
<td>832 (769-896)</td>
<td>812 (742-882)</td>
<td>.089</td>
<td>806 (716-896)</td>
<td>808 (744-872)</td>
<td>.485</td>
<td>840 (750-930)</td>
<td>820 (750-890)</td>
<td>.333</td>
</tr>
<tr>
<td>Trunk flexion (deg)</td>
<td>23.4 (18.3-27.4)</td>
<td>20.9 (17.1-23.8)</td>
<td>.003</td>
<td>22.2 (17.6-26.8)</td>
<td>18.9 (13.0-24.8)</td>
<td>.004</td>
<td>22.5 (18.7-27.3)</td>
<td>20.4 (14.3-26.5)</td>
<td>.008</td>
</tr>
<tr>
<td>Lateral Trunk Tilt (deg)</td>
<td>10.1 (2.3-17.9)</td>
<td>6.9 (1.9-12.0)</td>
<td>.252</td>
<td>9.0 (0-13.8)</td>
<td>4.2 (0-9.9)</td>
<td>.044</td>
<td>5.5 (0-13.9)</td>
<td>4.4 (0-8.9)</td>
<td>.131</td>
</tr>
<tr>
<td>Hip Shoulder Separation (deg)</td>
<td>49.1 (41.4-56.7)</td>
<td>43.5 (35.0-52.1)</td>
<td>.084</td>
<td>49.1 (37.8-56.0)</td>
<td>38.0 (30.1-45.9)</td>
<td>.023</td>
<td>44.2 (36.3-52.1)</td>
<td>38.8 (30.6-46.9)</td>
<td>.068</td>
</tr>
<tr>
<td>Maximum Elbow Valgus Torque (%BWxH)</td>
<td>3.1 (2.6-3.6)</td>
<td>2.8 (2.2-3.4)</td>
<td>.365</td>
<td>2.9 (2.3-3.3)</td>
<td>2.8 (2.3-3.3)</td>
<td>.233</td>
<td>2.7 (2.2-3.2)</td>
<td>2.5 (2.3-2.9)</td>
<td>.042</td>
</tr>
<tr>
<td>Maximum Shoulder Distraction Force (%BW)</td>
<td>120 (104-136)</td>
<td>105 (90-120)</td>
<td>.013</td>
<td>113 (95-130)</td>
<td>94 (84-104)</td>
<td>.120</td>
<td>106 (94-117)</td>
<td>93 (76-110)</td>
<td>.039</td>
</tr>
<tr>
<td>Maximum Ground Reaction Force (%BW)</td>
<td>217 (47)</td>
<td>193 (45)</td>
<td>.002</td>
<td>190 (39)</td>
<td>187 (43)</td>
<td>.131</td>
<td>197 (37)</td>
<td>181 (40)</td>
<td>.027</td>
</tr>
</tbody>
</table>

Means and standard deviation are reported as mean (SD), medians and interquartile range are reported as median (IQR); ES noted with 95% CI

BW = Body Weight, H = Height

*After Bonferroni correction, significance was set at $p < 0.0009$
Adolescent pitchers demonstrated greater maximum GRF pitching fastballs compared to change-ups, while non-pitchers had similar maximum GRF between all pitch types. Maximum GRF has a direct link to pitch velocity. During the pitching motion, the lower extremity serves as a counterforce to slow the lower extremity in order to create the trunk and upper extremity acceleration. Greater GRF allows for increased momentum and potential pitch velocity generation. However, non-pitchers did not demonstrate differences in maximum GRF between pitch types. One possible explanation is that pitchers produce improved resistance to knee flexion while producing an extension knee moment from front contact to release. Maximum GRF is produced during the late arm cocking phase. The ability of pitchers to resist knee flexion as lower extremity forces transition from a posterior to an anterior position during late cocking may allow for improved force transfer to the trunk and to ball propulsion. Non-pitchers may utilize increased knee flexion during the pitching motion instead of producing different forces to generate different pitch velocities for different pitch types. These discrepancies in lower extremity transfer may lead to increased injury risk; however, further research is required to understand the relationship between pitching as a primary or secondary position and its association with injury risk and optimal loading strategies.

STRENGTHS AND LIMITATIONS

There were several strengths and limitations in this study related to design and statistical analysis. This study utilized a standardized pitching biomechanical model with international guidelines, increasing the repeatability of this study. Reflective markers were placed directly on bony landmarks to minimize error due to skin movement between the markers and the anatomical landmarks being signified.

Incorporating adolescent baseball players that identify as primarily pitchers and non-pitchers increases the generalizability of these findings to all baseball players. While baseball players were constrained to a specific warm-up time, the exact warm-up exercises were personalized to replicate individual practice and game scenarios, which may reduce the repeatability of this investigation. These participants may be developing athletes, which may limit the external validity of these findings to other higher-level baseball populations. Further, skill level was not stratified in these analyses, potentially confounding these results.

A large cohort of 60 baseball players participated. Each pitch type was pitched in a specific order, which potentially could create an order effect. Not all baseball players threw each pitch type; while the authors attempted to control for this in the statistical methodology, this decreases the robustness of the data. Due to the multiple statistical analyses, a Bonferroni correction was utilized to decrease the probability of type 1 error. The low p-value threshold could limit the identification of important differences between groups. However, to assist in counteracting this possibility, effect size indices were calculated to note the overall strength of the effect.

CONCLUSION

Adolescent baseball players that identified primarily as pitchers had overall similar kinematics and kinetics in comparison to players that primarily identified as non-pitchers despite throwing at greater velocity for all pitch types. Adolescent pitchers produced greater trunk rotation velocity for fastballs in comparison to change-ups, while non-pitchers produced similar trunk rotation velocity between pitch types. Further, pitchers demonstrated decreased maximum GRF during change-ups in comparison to fastballs, while non-pitchers produced similar GRF between all pitch types. These data suggest that adolescent baseball players who identify primarily as pitchers may use favorable trunk and ground reaction force strategies for ball propulsion, but use similar upper extremity kinematics during pitching.

CONFLICTS OF INTEREST

No authors report any conflicts of interest.

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REFERENCES


Original Research

Shoulder Rotation Range of Motion and Serve Speed in Adolescent Male Volleyball Athletes: A Cross-Sectional Study

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Keywords: athletic performance, movement, athletes, range of motion, shoulder, volleyball

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Background
Throwing athletes present alterations in shoulder rotation range of motion (ROM), but not much is known about the relationship between these alterations and performance measurements in volleyball practitioners.

Purpose
To compare the passive ranges of motion of internal rotation (IR), external rotation (ER), and total rotation motion (TRM) of the shoulder in dominant and nondominant limbs of young volleyball athletes and to investigate their relationship with ball speed during serves with and without precision (inside and outside court, respectively). The possible association of anthropometrics and competitive practice time with these velocities was also investigated.

Study Design
Cross-sectional study.

Methods
Fifty-seven male volleyball athletes (mean age 17.11 ± 1.88 y; weight 74.68 ± 9.7 kg; height 1.87 ± 0.09 cm) were evaluated for shoulder IR and ER with a bubble goniometer and serve speed inside and outside court was measured with a radar gun. Simple and multiple regression analyses were applied to investigate associations of ROM, anthropometrics, and competitive practice time with serve speed.

Results
Dominant shoulders had diminished IR ROM compared to nondominant shoulders (59.1° ± 16.7° vs 66.4° ± 16.9°; p < 0.001) as well as diminished TRM (173.5° ± 31.8° vs 179.1° ± 29.9°; p < 0.001). Simple regression showed negative association between dominant ER and serve speed outside the court (p = 0.004). Positive associations existed between age and serve speed in both conditions (p < 0.001), BMI and speed inside (p = 0.009) and outside the court (p = 0.008), and between competitive practice time and speed inside (p = 0.008) and outside court (p = 0.005). However, multiple analysis confirmed only age (p < 0.001) and BMI to be associated with ball velocities (inside court p = 0.034; outside court p = 0.031).

Conclusion
The results of this study demonstrated that young volleyball athletes presented lower IR and TRM of the shoulder in the dominant upper limb. Age and BMI were directly associated with ball velocities when serving. Passive rotation ROM did not have a relationship with this performance measurement.

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INTRODUCTION

BACKGROUND

Throwing athletes have important morphological alterations of the shoulder as a result of the mechanical stimuli of sports movements. First observed in baseball pitchers, the main adaptations described affect the rotation range of motion (ROM) of the dominant shoulder, leading to greater ROM of external rotation (ER) and a concurrent internal rotation (IR) deficit, also known as glenohumeral internal rotation deficit (GIRD).\(^1\)

In throwing sports, these alterations are due to both soft tissue and bony adaptations. Retraction of the posterior articular capsule and rotator cuff muscles restrict humeral internal rotation and occur because of the eccentric stress that these structures receive during the deceleration phase of the arm during throwing.\(^2\) The ER gain can be due to loosening of the anterior capsule, related to the high amplitudes in the late cocking phase\(^2\) and due to the increased arm retroversion, which results from throwing torsional stress. This coincides with GIRD once the humeral axis is changed. In this way, total rotation motion (TRM, sum of internal and external rotation) is not altered.\(^3\)

Volleyball practitioners, who continuously repeat intense and fast movements of the dominant limb during actions such as the serve and spike, also experience ROM changes;\(^4,5\) asymmetries in rotator muscle strength,\(^4\) and postural differences compared to the nondominant side.\(^5\) In a recent literature review dealing with the volleyball population, seven out of nine studies verified the presence of GIRD, and five out of seven found an association between shoulder adaptations and injury or pain.\(^6\) However, the literature that addresses the possible relationship of these findings to volleyball performance measurements is still scarce. Some authors have investigated the ball speed during spike and the morphological aspects of the shoulder,\(^5,7\) but the serve and its association with ROM values has not yet been explored.

Therefore, the purpose of this study was to compare the passive ranges of motion of IR, ER, and TRM of the shoulder in dominant and nondominant limbs of young volleyball athletes, and to investigate their relationship with ball speed during serves with and without precision (inside and outside court, respectively). Possible association of anthropometric data and competitive practice time with these velocities was also investigated.

METHODS

STUDY DESIGN

This was a cross-sectional study, in agreement with the STROBE statement for observational studies. Shoulder rotation passive ROM and maximum serve speed of adolescent male volleyball athletes were measured to investigate associations. Dominant and nondominant rotation passive ROM measurements were also compared. Recruitment took place between 2015 and 2016 during two seasons in a training center in Sao Paulo, Brazil. The study was approved by the Research Ethics Committee of Federal University of Sao Paulo.

PARTICIPANTS

Participants were selected from an initial interview to match the eligibility criteria, which included volleyball athletes aged between 15 to 23 years. They must have trained for competition for at least one year; could not present any pain that could interfere with the assessment; could not have had previous surgery in the dominant shoulder; and could not be in physical therapy treatment for a complaint related to the shoulder. All participants and legally responsible guardians signed written forms consenting to their participation in the study.

VARIABLES

Variables that characterized the population were age, weight, height, BMI, competitive practice time, weekly training load, position on court, presence of previous injuries in dominant shoulder, IR and ER range of motion, TRM of dominant and nondominant upper limbs, and maximal serving speed with and without precision (inside and outside court, respectively).

PROCEDURES

The included athletes underwent a single assessment, which consisted of an initial interview followed by bilateral measurement of shoulder rotation ROM and serve speed in the order presented below.

Initial interview: Participants gave personal, demographic, and sports data, as well as reporting any shoulder injuries or pain.

Rotation ROM: Two trained physiotherapists conducted bilateral assessment to obtain passive glenohumeral IR and ER values. TRM was calculated by adding IR and ER values. The physiotherapists practiced the assessment methods for two months before the testing started, mentored by another physiotherapist with expertise in shoulder assessment. One therapist was responsible for stabilizing the shoulder anteriorly and taking it to the maximum range of rotation, while the other positioned a 12-in manual bubble goniometer (Prestige Medical®, Los Angeles, CA, USA) for measurement. Measurement was performed with each participant in the supine position with knees flexed, feet supported on the table, with shoulder to be evaluated placed at 90° of abduction, with forearm in the neutral position.\(^8\) The reliability of these measures was assessed in a pilot study, with a confidence index of 0.9.

Serve speed: Serve speed was measured using a speed radar gun (Bushnell Velocity™) with an accuracy of \(\pm\) 2 km/h and a speed range of 16-177 km/h at 27 m. The athletes were positioned 2 m behind the end line of the court for the execution of the serves. The evaluator was positioned be-
Beyond the opposite end line, 20 m away from the athlete, and aimed the radar toward the participant (Figure 1). To obtain maximum serve speeds involving precision, the participants were informed that they should serve with the maximum force possible, seeking to reach the interior of the opposite court. Then, in order to obtain maximum speeds without precision, they were asked to serve with as much force as possible, seeking to hit off-court. For both conditions, the serve was executed without jumping, in view of its influence on speed.9 The ball could not touch the net; the participants repeated the execution until three values with variation of up to 10% between the attempts were obtained, and an interval of 10 seconds between them was given. A submaximal test for each condition was performed as a procedure for familiarization. The reliability of this measurement was assessed in a pilot study whose confidence index was 0.9.

BIAS

It was opted to evaluate ROM first, followed by measurement of serve speed, while considering the possible acute effects of the movement in the amplitude measurements.10

STUDY SAMPLE SIZE

The number of participants was achieved by initial calculus of the sample size, which was calculated using standard deviation values of 8.53 for IR, 7.81 for ER, and 9.04 for TRM obtained in a previous study.11 With a power of 80% and significance of 5%, the minimum number of athletes required for the present study were 30, 5, and 3, according to the standard deviations of IR, ER and TRM, respectively.

STATISTICAL METHODS

Data were analyzed using the Statistical Package for Social Sciences (SPSS) software for Windows version 18.0 (SPSS, Inc., Chicago, Illinois). The anthropometric and sports characteristics, measures of shoulder ROM and maximum serve speed were described by mean and standard deviation for the total sample. The number of athletes who reported previous injuries in the dominant shoulder, and the number of athletes per position, were given in absolute values and percentage. After checking for normality, differences between dominant and non-dominant upper limb ranges of motion and between on-and off-court ball velocities were investigated through paired t-tests. Associations between the explanatory variables (age, height, BMI, competitive practice time, dominant IR, and dominant ER) and serve velocities were verified using a simple linear regression model. This model was later adjusted to the multiple approach using the stepwise method of variable selection,12 in accordance with a previous study with similar methodology.5 The results were presented as an estimated coefficient and standard error, and a significance level of 0.05 was adopted for all analysis.

RESULTS

PARTICIPANTS

The study included 57 young male volleyball players. The descriptive data characterizing the sample, including ROM data and serve speed, are presented in Table 1.

RANGE OF MOTION

Passive ROM comparisons between the dominant and non-dominant limbs are shown in Table 2. IR and TRM were sig-
Table 2: Comparisons between dominant and non-dominant ROM and ball speed in two serve situations

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean (CI 95%)</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIR - NDIR</td>
<td>-7.2 (-9.5; -4.9)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DER – NDER</td>
<td>1.6 (1; 4.2)</td>
<td>0.219</td>
</tr>
<tr>
<td>DTRROM – NDTRROM</td>
<td>-5.6 (-8.5; -2.7)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ball speed inside court – Ball speed outside court</td>
<td>-10.3 (-11.6; -9.1)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

CI = confidence interval; DIR = dominant internal rotation; NDIR = non-dominant internal rotation, DER = dominant external rotation; NDER = non-dominant external rotation; DTRROM = dominant total rotation range of motion; NDTRROM = non-dominant total rotation range of motion

*p statistically significant difference at p < 0.05

Table 3: Results of simple linear regression: association between demographics and dominant ROM and ball speed in two serve situations.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Ball speed inside court (km/h)</th>
<th>Ball speed outside court (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>1.26 (0.27)</td>
<td>1.71 (0.32)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>0.81 (0.30)</td>
<td>1.02 (0.37)</td>
</tr>
<tr>
<td>Competitive practice time</td>
<td>0.07 (0.02)</td>
<td>0.09 (0.03)</td>
</tr>
<tr>
<td>DIR (degrees)</td>
<td>-0.02 (0.04)</td>
<td>0.609</td>
</tr>
<tr>
<td>DER (degrees)</td>
<td>-0.03 (0.03)</td>
<td>-0.11 (0.04)</td>
</tr>
</tbody>
</table>

SE = standard error of mean, BMI= body mass index, DIR = dominant internal rotation, DER = dominant external rotation, *statistically significant difference at p < 0.05

Table 4: Results of linear regression in multiple analysis

<table>
<thead>
<tr>
<th>Variables</th>
<th>Ball speed inside court (km/h)</th>
<th>Ball speed outside court (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>1.14 (0.27)</td>
<td>1.56 (0.32)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>0.58 (0.27)</td>
<td>0.71 (0.32)</td>
</tr>
</tbody>
</table>

SE = standard error of mean, BMI= body mass index *statistically significant difference at p < 0.05

nificantly lower for the dominant limbs, whereas ER did not differ between the sides.

SERVE SPEED

Table 2 also shows the comparison of the velocities of the ball in the two serve situations. The speed was 10.3 km/h higher when the athletes were asked to purposely hit out of the court.

ASSOCIATIONS WITH SERVE SPEED

The results of the simple linear regression are presented in Table 3. An indirect association between the range of the dominant ER and the maximum speed of the ball outside court was found, so that the increase of one degree in ER represented a decrease of 0.11 km/h in velocity (p = 0.004).

Evidence of a direct association with ball velocities was found for age in both inside and outside court conditions (p < 0.001), for BMI within the court (p = 0.009) and outside it (p = 0.008), and for competitive practice time both within the court (p = 0.008) and outside it (p = 0.003).

Table 4 presents the results of the multiple linear regression. After adjustment of the models, the variables age and BMI were selected because they explained 34.2% of the variability of the velocity measurements within the court, and 39.2% of the variability of the velocity measurements outside the court.

DISCUSSION

The purpose of the present study was to compare the shoulder rotation passive ROM of the dominant and nondominant sides of young male volleyball players and to investigate the relationship between these measurements and ball speed when serving. The association of this performance measure with anthropometrics and competitive practice...
time was also investigated.

There were no significant differences in ER measures thus, the smaller TRM on the dominant side was due to lower IR. Other studies also verified the presence of GIRD in volleyball athletes.11,13,14 On the other hand, several authors15–17 have verified the presence of GIRD associated with higher ER values on the dominant side. Other authors have also found similar ROM between sides for both internal and external rotation.18,19 Inconsistency among the findings may be due to variations in the ROM assessment methods, differences in the populations studied, sports practice level, gender, and the fact that some studies were carried out with beach volleyball athletes.11,17

The results of the current study identified a significant IR deficit, reinforcing the presence of specific musculoskeletal adaptations of the shoulder of the volleyball athlete, which have already been described in other throwing sports.1,20 When an isolated IR deficit is present without gain in ER, compared to nondominant side, this deficit may be related to changes within the posterior soft tissues of the shoulder, such as the articular capsule and rotator cuff muscles. This is due to the high eccentric loads that these structures are subjected to during the deceleration phase of the arm in throwing athletes.2 When IR deficit is comorbid with ER gain, bony adaptations can be present because of changes in the humeral axis. The findings of the present study suggest that, in general, this population of young volleyball male players did not have enough repeated chronic strain to lead to bony alteration, although bony alteration was not directly measured. However, it could be present later, in more experienced players who have taken part in volleyball training programs over more years.

Serve velocities on and off the court differed significantly. According to Fits’ Law, the accuracy of movement toward a target decreases as the velocity of motion increases, and this relationship has already been verified under various conditions.21 It was expected and confirmed that in the outside court serve condition, the athletes would attain higher serving velocities, as it is a condition in which less precision is demanded. This difference was important because in the multiple regression model, the coefficient of determination for age and BMI (39.2%) explained the variability of off-court velocities most clearly. Despite the differences found in velocities during serves with and without precision, there is no consensus on how to better assess the speed of a serve in volleyball. Two studies have used radar speed to evaluate the spike.5,7 Among studies that have evaluated serve speed, one does not describe the methodology used,18 and another did so with the use of a radar device on a tripod during a professional tournament.9

Simple regression analysis showed an indirect association between serve speed and ER on the dominant side when athletes were asked to hit the ball out of court; that is, there was a tendency that the higher the ER, the lower the velocity of the ball. These results are opposite from those observed in baseball pitchers: those with the highest ball speeds present higher degrees of ER.2 These associations had not been investigated in volleyball athletes until the present study. Forthomme et al.7 investigated factors correlated with volleyball spike velocity and assessed shoulder rotation ROM, but they did not investigate correlational factors. Shoulder rotation ROM was assessed only to describe the sample and verify differences between sides. Challoumas et al.5 investigated some shoulder morphological measurements, such as scapular lateralization and dorso-inferior capsule laxity and verified their correlation with spike speed, but shoulder rotation ROM was not investigated.

One possible explanation for the association found in the simple regression between ER and serve speed is that in young athletes undergoing shoulder adaptations, higher ER angles could represent less control over the joint, negatively impacting the kinetic chain energy transfer and power production when serving. Authors that have verified increased dominant shoulder ER in volleyball athletes have not investigated its association with serve or spike speed;4,15–17 therefore, the association found in the present study is still difficult to compare to existing literature. Additionally, correlation between ER and serve speed was not confirmed in the multiple regression model. It is possible that higher shoulder ER could be present in younger athletes with lower BMIs. This may negatively impact serve speed, as seen in the multiple regression analysis. Although the relationship of shoulder morphology and physical performance data with velocity measures in volleyball has been investigated before, ROM and serve speed have not been explored. It has already been verified that spike speed is positively correlated with the peak torque of the internal rotators of the dominant shoulder, jumping capacity, and BMI,7 and that there is a positive relationship between the spike speed and the shoulder posterior capsule’s state of contracture as measured by a horizontal adduction test.5 Differently from the present study results, Schwab et al.18 did not find a relative relationship between shoulder measurements and serve speed in the simple regression. But they observed elite volleyball players and the shoulder measurement was humeral torsion. In addition, the methods to assess serve speed were not explained and took place months before shoulder assessment.

Age, BMI, and competitive practice time were the variables positively associated with ball velocity according to the simple regression analysis. In the multiple regression model, only age and BMI were associated with serve speed, which means they explained the variability of speeds most clearly. Nevertheless, the determination coefficients were weak, which means the interpretation of the results (considering only what was kept in the final model) may be subject to significant errors.

Muscle mass and strength, coordination, and refinement of serving technique could be among the factors that could explain the results, but none of these were measured in this research design. These questions need to be tested in future randomized clinical trials to investigate the use of isokinetic machines for strength training and their effects on serve speed. Furthermore, we suggest investigating the effects of specific serve skills training protocols to improve serve speed.

In the present study, only young male volleyball players were observed; therefore, the results cannot be generalized to all volleyball athletes. The measurements obtained for shoulder ROM do not necessarily represent the amplitudes that may be reached during the serve movement in a more
functional context. Additionally, while a radar gun was used, there is no consensus on how to best assess serve speed.

Future studies should evaluate athletes who practiced volleyball longer and in whom musculoskeletal adaptations are more evident. These studies should also evaluate the relationship between ROM adaptations, such as diminished IR, and specific measures of sport performance. To better understand the function of the shoulder in this population, studies involving kinematics should investigate whether the active rotation motion reached during the execution of the serve relates to serve speed and whether these amplitudes are at all similar to the passive measures. In addition, studies should investigate the function of other joints in the transfer of mechanical energy within the kinetic chain of the serve motion and their relationship with this performance measure.

CONCLUSION

The results of this study indicate that young male volleyball athletes present with decreased internal rotation and total rotation motion of the shoulder in the dominant upper limb as compared to the non-dominant limb. Age and BMI were the variables directly associated with ball velocities in serving and further justified its variability, explaining 34.2% of the velocities within the court and 39.2% outside the court. Passive rotation ROM does not seem to have a relationship with serving speed.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

FUNDING

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REFERENCES


Original Research

Shoulder Rotational Strength Profiles of Danish National Level Badminton Players

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Keywords: age, badminton, dynamometer, overhead athletes, shoulder

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International Journal of Sports Physical Therapy

Background

Increased age has been shown to be associated with weaker external rotators and stronger internal rotators of the shoulder in pitchers and tennis players. Whether this age-associated change is present in elite badminton players is unknown.

Purpose

To compare the internal and external rotation strength of the shoulder in adolescent and adult elite badminton players.

Study design

Cross-sectional.

Methods

Thirty-one adolescent (12 females aged 16.8 ± 1.6 years and 19 males aged 17.1 ± 1.6 years) and 29 adult (10 females aged 25 ± 2.9 years and 19 males aged 26.2 ± 4.6 years) national level badminton players were tested pre-seasonally for external rotation (ER) and internal rotation (IR) isometric muscle strength bilaterally, using a hand-held dynamometer. Within-group ER to IR strength ratios were calculated (ER/IR×100%).

Results

The adolescents had stronger shoulder ER than the adults on both sides (p < 0.05). The adult males tended to have stronger IR of the dominant shoulder than the adolescent males (p = 0.071). In the dominant shoulders, the strength ratios for adult females and males were 77% and 78%, respectively, while the same ratio for adolescent females and males were 85% and 99%, respectively. In the non-dominant shoulders, the ER/IR strength ratios for adult females and males were 90% and 87%, respectively, while the ratios for adolescent females and males were 116% and 102%, respectively.

Conclusion

This study is the first to demonstrate that in shoulder injury-free national team badminton players, adolescents have stronger shoulder ER than adults on both sides. Therefore, increased age appears to be associated with weaker shoulder ER muscles in elite badminton players.

Level of evidence

3b.

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INTRODUCTION

Shoulder injuries are common in upper extremity sports, particularly at the elite level.\textsuperscript{1–5} Many badminton players with shoulder pain continue their sport despite the risk of developing chronic conditions, such as subacromial pain syndrome and rotator cuff tendinopathy.\textsuperscript{1–6} Thus, knowledge of shoulder profiles of upper extremity athletes is of great value in an injury preventive perspective.

In various upper extremity sports (baseball pitching, swimming, tennis and golf), the overhead throwing type motion is somewhat similar according to studies of motion and electromyography.\textsuperscript{7–9} During the act of throwing, the eccentric forceseloads generated put excessive mechanical stress (load divided by tissue cross-sectional area) on the rotator cuff tendons and muscles, the capsule and the ligamentous structures of the shoulder,\textsuperscript{10} and these repetitive high loads may lead to overuse tendon injuries.\textsuperscript{11} It has been suggested that shoulder pathology in overhead sports is associated with external rotation (ER) muscle weakness\textsuperscript{12–14} and imbalance in the ratio between ER to internal rotation (IR) strength.\textsuperscript{15–17} Several authors have demonstrated ER muscle weakness of the dominant (DOM) shoulder compared to the non-dominant (NDOM) shoulder in high school and professional throwers\textsuperscript{18,19} and other overhead athletes.\textsuperscript{20}

The rotational shoulder strength of badminton players has only been minimally studied. Ng and Lam examined recreational badminton players and observed that male players have lower ER to IR strength of the DOM shoulder compared to the NDOM shoulder.\textsuperscript{21} In young elite badminton players, the rotational strength appears to be similar between the DOM and NDOM shoulders in the males, while there was a greater IR strength on the DOM side that was not balanced by a greater ER strength in females.\textsuperscript{17} The shoulder rotational strength profiles of shoulder injury-free adolescent and adult national level badminton players has not been compared previously.

Increased age has been associated with decreased shoulder strength, including of the internal and external rotators, in the more general population in the age range 20 to 39 years.\textsuperscript{22} It is possible that testosterone, which peaks at the average age of 19 and 17 years in males and females, respectively, and subsequently declines, explain these observations.\textsuperscript{23,24} Therefore, the present study was conducted to compare the ER and IR strength of the shoulder in adolescent and adult elite badminton players. It was hypothesized that compared to adult badminton players, adolescent badminton players have stronger shoulder ER and IR.

METHODS

PARTICIPANTS

Thirty-one adolescents; 12 females aged 16.8 ± 1.6 years and 19 males aged 17.1 ± 1.6 years, and 29 adults; 10 females aged 25 ± 2.9 years and 19 males aged 26.2 ± 4.6 years (mean ± standard deviation) from the Danish national badminton team volunteered and participated in this cross-sectional study as part of a pre-season screening in 2005. Subject consent was given in accordance with the policy statements of American College of Sports Medicine and the Danish Society of Sports Medicine. The complete methods are described elsewhere.\textsuperscript{17}

The players underwent a screening for injuries and were only allowed to participate in the study if they were free from any current and previous shoulder injury. This screening included an evaluation of the spine and shoulders, including the Hawkins-Kennedy test, Jobe’s test, apprehension test, O’Brien’s test and foraminal compression/distraction test.\textsuperscript{25,26} One adolescent female player was excluded due to joint instability of the NDOM shoulder.

ASSESSMENTS

The strength measurements were performed with a handheld dynamometer (HHD) (J-Tech Power Track® dynamometer, JTECH Medical, Salt Lake City, UT, USA) in the same test position as used in other studies.\textsuperscript{27,28} Shoulder ER and IR strength assessments were conducted with the participants lying in supine position with the shoulder abducted 90° and in the scapular plane.\textsuperscript{27,29} The participants’ elbows were flexed 90° and the examiner stabilized the upper arm by pressing it down toward the examination table. The participants grasped the table with their non-testing arm, thereby providing additional stabilization. This position was selected due to its similarity with the badminton smash, to obtain maximum strength values and minimize risk of shoulder injury.\textsuperscript{30} The testing angle was checked visually. In the ER test, the participants externally rotated their shoulder against the HHD while the HHD was located proximal to the ulnar styloid process. In the IR test, the participants internally rotated their shoulder against the HHD while the HHD was located proximal to the ulnar styloid process. In both the ER and IR tests, the glenohumeral rotation was placed at midrange/neutral position, so the forearm was elevated to a vertical position.\textsuperscript{17} These were isometric “make tests” consisting of a 5–6 s maximum voluntary contraction (MVC) by the player. The “make test” is isometric in nature and therefore associated with less risk of muscle damage or soreness compared with the “break test”. The specific HHD can register 0–500 N with a sensitivity of 0.2 N and it was calibrated prior to each trial. Two examiners tested the players blinded to side dominance, and for practical reasons, one examiner tested the adolescent group and another examiner tested the adult group. Inter-tester-reliability was thus evaluated. The player warmed up by performing 15 repetitions of ER and IR with a 1 kg dumbbell in side lying prior to the strength assessments, without becoming fatigued. The players were instructed in a standardized manner only to move their testing arm during the assessments. Prior to the trials, the players were reminded in a standardized manner of the importance of providing their MVC. A standardized verbal encouragement was given during each effort. A mean of three MVCs was recorded for IR and ER each. A 20–30 s pause was mandatory between each trial.\textsuperscript{22} The order of assessments was constant, i.e., right ER, right IR, left ER and left IR.\textsuperscript{31} Torque was calculated as strength (N) ¥ full arm length (m) and normalized to body weight (N m/kg). Full arm length was measured just proximal to the ulnar styloid process and just below to the acromion.\textsuperscript{17}
Table 1: Participants’ age, arm length and body weight. Values are mean ± standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th></th>
<th>Males</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Number of players</td>
<td>Adolescents</td>
<td>Adults</td>
<td>Adolescents</td>
<td>Adults</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>10</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Age (years)</td>
<td>16.8 ± 1.6</td>
<td>25.0 ± 2.9</td>
<td>17.1 ± 1.6</td>
<td>26.2 ± 4.6</td>
</tr>
<tr>
<td>Arm length (m)</td>
<td>0.54 ± 0.04</td>
<td>0.55 ± 0.03</td>
<td>0.60 ± 0.03</td>
<td>0.60 ± 0.03</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>61.1 ± 7.0(*)</td>
<td>65.0 ± 6.3</td>
<td>74.2 ± 7.4(†)</td>
<td>78.4 ± 5.9</td>
</tr>
</tbody>
</table>

Female adolescents versus female adults: (*) p = 0.139
Male adolescents versus male adults: (†) p = 0.065

The selected test position has proven sensitive to detecting side-to-side differences. The HHD assessment is valid and has shown to be more precise and sensitive to ER muscle weakness in the same test position when compared to an isokinetic strength test instrument. Also, assessment with HHD has proven to be intra- and inter-rater reliable.

STATISTICAL ANALYSIS

Within- and between-group statistical comparisons were made with Wilcoxon’s rank-sum test and Mann-Whitney U-test, respectively, since the data by visual inspection appeared not to be normally distributed. p-values of < 0.05 were considered to be statistically significant. Within-group ER to IR strength ratios were calculated using the formula ER/IR×100%. Intra- and inter-rater reliability of the strength measurements were calculated and reported as typical error. All statistical analyses were performed using the software package GraphPad Prism® 6.0 (San Diego, CA, USA).

RESULTS

INTRA- AND INTER-RATER RELIABILITY

For adolescents, the intra-rater reliability of the measurements was substantial with a typical error in percentage for IR and ER strength assessments of 5.4% (3.9-6.9%) and 5.4% (5.3-6.8%), respectively. The typical error in percentage for the IR and ER strength assessments of the adults was 4.6% (2.9-5.3%) and 4.8% (3.9-5.5%), respectively. A Spearman’s rank correlation coefficient (r) value was calculated to determine the strength of the relationship between the two highest values. The r-value was 0.99. There were no systematic differences (paired t-test) between the two highest values. Inter-rater reliability on seven participants demonstrated a typical error in percentage for IR strength measurements of 6.8% and for ER strength measurements of 6.2%. There were no significant differences between the two examiners in any of the testing movements.

BODYWEIGHT AND ARM LENGTH OF THE GENDER AND AGE GROUPS

The body weight and arm length of the gender and age groups are presented in Table 1.

EXTERNAL AND INTERNAL ROTATIONAL SHOULDER STRENGTH

The males were generally stronger than the females. The adolescents had stronger shoulder ER than the adults (p < 0.05). The adolescent and adult females and the adult males had stronger IR of the DOM shoulder compared to the NDOM shoulder (p < 0.05). Expressed as a percentage, the adolescent females and males had 25% and 13% stronger DOM and 27% and 15% stronger NDOM shoulder ER than the adult females and males, respectively (Table 2). The adult males tended to have 12% stronger IR of the dominant (DOM) shoulder than the adolescent males, although this was not statistically different (p = 0.071) (Table 2). In the DOM shoulders, the ER/IR strength ratios for adult females and males were 77% and 78%, respectively, while the ratios for adolescent females and males were 85% and 99%, respectively. In the NDOM shoulders, the ER/IR strength ratios for adult females and males were 90% and 87%, respectively, while the ratios for adolescent females and males were 116% and 102%, respectively (Table 2 and Figure 1).
Table 2: The badminton players shoulder torque normalized to Nm/kg. Values are mean ± standard deviation.

<table>
<thead>
<tr>
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<th>Females</th>
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<th>Males</th>
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<tbody>
<tr>
<td></td>
<td>Adolescents</td>
<td>Adults</td>
<td>Adolescents</td>
<td>Adults</td>
<td></td>
</tr>
<tr>
<td>ER DOM</td>
<td>1.11 ± 0.5† (††)</td>
<td>0.89 ± 0.19</td>
<td>1.39 ± 0.20§</td>
<td>1.23 ± 0.31</td>
<td></td>
</tr>
<tr>
<td>ER NDOM</td>
<td>1.19 ± 0.19†</td>
<td>0.94 ± 0.13</td>
<td>1.44 ± 0.28§</td>
<td>1.25 ± 0.31</td>
<td></td>
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<tr>
<td>IR DOM</td>
<td>1.31 ± 0.31§§</td>
<td>1.16 ± 0.20§§</td>
<td>1.40 ± 0.30(‡)</td>
<td>1.57 ± 0.30§§</td>
<td></td>
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<tr>
<td>IR NDOM</td>
<td>1.03 ± 0.19</td>
<td>1.05 ± 0.18</td>
<td>1.37 ± 0.26</td>
<td>1.44 ± 0.20</td>
<td></td>
</tr>
<tr>
<td>ER/IR ratio DOM</td>
<td>0.85 ± 0.21† §§</td>
<td>0.77 ± 0.16(#)</td>
<td>0.99 ± 0.18**</td>
<td>0.78 ± 0.14(‡‡)</td>
<td></td>
</tr>
<tr>
<td>ER/IR ratio NDOM</td>
<td>1.16 ± 0.11†</td>
<td>0.90 ± 0.13</td>
<td>1.02 ± 0.14**</td>
<td>0.87 ± 0.16</td>
<td></td>
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</table>

ER: External rotation, IR: Internal rotation, DOM: Dominant shoulder, NDOM: Non-dominant shoulder
Female adolescents versus female adults: * p < 0.05; † p < 0.01
Male adolescents versus male adults: (‡) p = 0.071; ‡ p < 0.05; ** p < 0.01
Dominant versus non-dominant side: (††) p = 0.067; (‡‡) p = 0.065; (‡‡‡) p = 0.061; §§ p < 0.05

DISSCUSSION
The objective of this study was to describe and compare the shoulder rotational strength of adolescent and adult elite badminton players. The main findings were that the adolescent players had stronger shoulder external rotation (ER) than the adult players on both sides. These first data suggest that advanced age is associated with weaker shoulder ER in elite adult badminton players, which may warrant strengthening of the ER muscles as a player ages, which could be a potential strategy to reduce the risk of future shoulder injury.

BADMINTON INDUCED ADAPTATIONS
The badminton smash and the adaptations to the shoulder muscles are similar in other extremity sports involving the throwing motion.7,36 As mentioned, the adolescents in the present study were stronger than the adults, in terms of shoulder ER of both sides. Furthermore, the adult females and males had ER/IR strength ratios of 77% and 78% of the DOM shoulder, respectively, while the ratios were considerably more balanced (closer to 1:1) in the adolescent groups. These results are consistent with those of elite tennis players (e.g., training type, intensity and frequency) in the different age and gender groups. The strength and power of the IR muscles may increase as an adaptation to the smashing motion. One function of the ER muscles is to decelerate the arm in throwing of follow through; they do not increase their strength proportionally like the IR muscles, probably due to the size of muscle-tendon structure. The ER rotator cuff muscle-tendons are smaller than the IR rotator cuff muscles-tendons, which could explain why some shoulder injuries occur from repetitive smashing and throwing.

It should be noted that, while weak ER strength was associated with higher risk of shoulder injury in a cohort study of 144 baseball pitchers (p = 0.005)12 and in a cohort of 206 elite male handball players (odds ratio = 1.29),13 such relation was not confirmed in a cohort of 329 elite handball players (odds ratio = 1.05).14

GENDER DIFFERENCES
As expected, in the present study, the males were stronger than the females after adjustment for body weight, and this can be explained by the physical sex difference. The results of the female age groups should be interpreted with caution, as the analyses may lack statistical power due to the relatively small sample sizes. Notably, Fahlstrom et al. observed that in world class badminton players, females generally perform less shoulder training than males.1 Thus, it was hypothesized that the same was evident in the current study and that it would be reflected in the results. However, based on the present data, it can be hypothesized that preventive strength training with proper restitution to stabilize and balance the rotator cuff is even more important in females than in males to reduce the risk of overuse injury in the shoulder.39,40

ADDITIONAL CONSIDERATIONS AND LIMITATIONS
This study has some limitations worth mentioning. It is cross-sectional in design and had a relatively small sample size, which prohibits conclusions about causality between shoulder rotational strength and aging with badminton play; future studies should be prospective in design and risk of injury should be correlated with shoulder strength.

Furthermore, shoulder strength was only tested isometrically, however, measuring eccentric strength would have provided more valid results.3,16,33 Also, the moment arm was measured just proximal to the ulnar styloid process and just below the acromion (full arm length) instead of the forearm length, thereby likely overestimating ER and IR torque.17
The number of hours played was not recorded and this may be a confounding factor; by recording hours played, it may be possible to separate badminton specific muscle strength/weakness adaptations from general aging factors. It is plausible that hours played is associated with weaker ER and stronger IR of the DOM shoulder due to repeated forceful internal rotational movements that may leave the smaller external rotators vulnerable to large eccentric forces.

CONCLUSION

This study is the first to demonstrate that in injury-free national team badminton players, adolescent players have greater isometric shoulder ER strength than adult players on both sides. It is plausible that increased age is associated with weaker shoulder ER in elite badminton players.

FUNDING

No outside funding was received for this work.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

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International Journal of Sports Physical Therapy
REFERENCES


Original Research

The Effect Of Mild Exercise Induced Dehydration On Sport Concussion Assessment Tool 3 (SCAT3) Scores: A within-subjects design.

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Keywords: balance, cognition, concussion management, movement system

https://doi.org/10.26603/001c.21534

International Journal of Sports Physical Therapy

Background

Sports-related concussions are prevalent in the United States. Various diagnostic tools are utilized in order to monitor deviations from baseline in memory, reaction time, symptoms, and balance. Evidence indicates that dehydration may also alter the results of diagnostic tests.

Purpose

The purpose was to determine the effect of exercise-induced dehydration on performance related to concussion examination tools.

Study Design

Repeated measures design.

Methods

Seventeen recreationally competitive, non-concussed participants (age: 23.1±3.1 years, height:168.93±10.71 cm, mass: 66.16 ± 6.91 kg) performed three thermoneutral, counterbalanced sessions (rested control, euhydrated, dehydrated). Participants were either restricted (0.0 L/hr) or provided fluids (1.0 L/hr) while treadmill running for 60 min at an intensity equal to 65-70\% age-predicted maximum heart rate (APMHR). The Sport Concussion Assessment Tool 3 (SCAT3) was utilized to assess symptoms, memory, balance, and coordination.

Results

Statistically significant differences were seen among sessions for symptom severity and symptom total. The rested control session had significantly lower values when compared to the dehydrated session. Additionally, the symptom total in the rested control was significantly lower than the euhydrated condition as well. No statistically significant differences were seen for the BESS or memory scores.

Conclusions

Mild exercise-induced dehydration results in increased self-reported symptoms associated with concussions. Clinicians tasked with monitoring and accurately diagnosing head trauma should take factors such as hydration status into account when assessing patients for concussion with the SCAT3. Clinicians should proceed with caution and not assume concussion as primary cause for symptom change.

Level of evidence

Level 3

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INTRODUCTION

Sports-related concussions and the proper care of athletes with concussion symptoms is a growing concern in the healthcare field. Epidemiological analyses of sports-related concussions in the United States estimate there are between 1.6 and 3.8 million incidents per year.\(^1\) While cognitive deficits as a result of a single concussive event may not result in long-term impairments, repetitive concussions or a subsequent concussion prior to adequate recovery has been reported to lead to longer lasting effects.\(^2\)\(^-\)\(^3\) Therefore, properly identifying concussed patients and removing them from participation is critical to long term brain health. Further, due to the risks and high incidence rate of concussion, proper diagnosis is vital for proper administration of care and improved return to play timelines for athletes. Concussion detection tools utilize deviations in various symptoms, including short- and long-term memory, reaction time, and postural stability, from a baseline to determine likelihood of a concussive event.\(^4\)\(^-\)\(^5\) However, the nature of sport and physical activity may produce extraneous conditions that may result in similar symptoms or conditions that may disrupt the ability of a health care professional to accurately detect and manage patients with a concussion.\(^6\)\(^-\)\(^9\)

Mild dehydration (< 2% loss in BM) has also been reported to alter variables examined to determine concussion.\(^10\)\(^-\)\(^12\) Landers, Arent, and Lutz\(^13\) reported non-significant cognitive disturbances amongst various tests for wrestlers who voluntarily dehydrated themselves for competition weight, whereas Lieberman et al.\(^14\) reported significant changes in reaction time, memory, attention, and reasoning in response to exercise-induced dehydration in a hyperthermic environment. These results indicate that exercise-induced dehydration, especially in the heat, may hinder cognitive performance. Similarly, Patel and colleagues\(^15\) reported significant changes in visual memory, fatigue, and severity of symptom (headaches, dizziness, feeling slowed down, difficulty remembering, and difficulty concentrating) scores amongst collegiate wrestlers following bouts of exercise-induced dehydration. Additionally, Weber and colleagues\(^8\) also found deviations in the Balance Error Scoring System (BESS) and the Graded Symptoms Checklist (GSK) following bouts of weight cutting techniques and wrestling practice amongst collegiate wrestlers.

On-field concussion tests are conducted on the field of play under conditions where exercise-induced dehydration may play a role in influencing the diagnosis. The suggested on-field concussion examination tool, the Sport Concussion Assessment Tool 3 (SCAT3), utilizes the common detection methods of concussion: attention, memory, balance and reaction time.\(^4\) The detection tools need to be able to determine the likelihood of a concussion to allow proper management. Ideally, concussion examination techniques will be both sensitive and specific allowing practitioners to be confident in clinical decisions. Therefore, the purpose of this study was to determine the effect of exercise-induced dehydration on cognitive performance as detected by the SCAT3.

METHODS

The current study used a counterbalanced repeated-measures design to investigate the effect of exercise-induced dehydration on neuropsychological performance and postural stability as detected by the SCAT3.

PARTICIPANTS

For the experiment, a total of 17 recreationally competitive volunteers consisting of seven males (25.0±3.7 yrs; 176.77±5.12cm; 68.62±3.92kg) and 10 females (21.8±1.9yrs; 162.82±9.98cm; 64.38±8.16kg), who regularly participated in 60 minutes of aerobic exercise three to four days per week, were recruited. The participants were excluded if they reported history of previously diagnosed concussion, heat-related illness, back and neck injury, cardiovascular disease, vestibular dysfunction, history of ADHD or ADD, dyslexia and other learning disabilities, or any lower extremity injury that would inhibit balance. All participants were required to read and sign a PAR-Q, a Medical History Questionnaire, as well as read and sign an Informed Consent Form approved by the Institutional Review Board at the University of Lynchburg prior to participation.

PROTOCOL

Participants completed three counterbalanced testing sessions separated by at least 72 hrs. Each subject was required to wear shorts, a shirt, socks, undergarments, and shoes during each training session and were asked to wear the same garments for each subsequent testing session. Participants were expected to come hydrated but were given no guidance on diet and they were not asked to track their diet via a journal.

Prior to attending the first session to get a baseline score, the participants were required to refrain from strenuous exercise, alcohol, and caffeine for 24 hours. Upon arrival to the laboratory and completion of the PAR-Q and Informed Consent Form, participants provided a 60- to 120-mL urine sample to determine urine specific gravity (USG, Palm Abbe 202X, Misco, Cleveland, OH). Anthropometric measurements including nude mass were determined via an electronic floor scale (BWB-800S, Tanita, Tokyo, Japan), a standing stadiometer (Seca, Hamburg, Germany), and body composition estimations via a Siri three-site skinfold measurement using handheld calipers (Lange, Cambridge, MA). Participants were excluded from testing if their USG was greater than or equal to 1.020, which would classify them as already dehydrated.

Participants performed two exercise sessions and a baseline session in counterbalanced order. The baseline (control) session consisted of participants resting and consuming fluid ad libitum for 60 min prior to completing the data collection protocol. Each exercise session was performed on a motorized treadmill (Full Vision TMX425 Trackmaster, Drive Newton, KS) at an incline of 1.0% grade and a speed that elicited an average of 65% to 70% of age-predicted maximum heart rate (APMHR) as measured by an attached heart rate monitor chest strap and watch (validity = 0.97-1.0; Polar WearLink® 31 transmitter and Polar RS400, International Journal of Sports Physical Therapy
Kempele, Finland)\textsuperscript{16} for 60 minutes.

Prior to each testing session, participants provided a 60- to 120 mL urine sample and performed a nude weight. In randomized order, participants performed the aforementioned exercise protocol in a thermoneutral environment with restricted water intake (dehydrated) and required fluid consumption of 1 L, via four 250 mL doses every 15 min (euhydrated). After the 60-minute exercise protocol, participants performed a five-minute cool down at self-selected pace. After the cool down, participants provided a 60- to 120- mL urine sample and had their body mass measured after towel ing dry. Hydration status post-test was determined as the percent change of body mass pre-test to post-test.

Following baseline hydration measurement, participants completed the SCAT3. The SCAT3 is the recommended on-field concussion assessment tool\textsuperscript{13} and contains a symptom checklist, the Standardized Assessment of Concussion (SAC), and a modified version of the Balance Error Scoring System (BESS). Scoring is the sum total of scores in each test within the SCAT3. Symptom checklist is scored as both present or absent. Symptom total is scored as the presence of the symptom, providing a total number of symptoms (max. score: 22) and severity score, summing the magnitude of each symptom (max. score: 132). The higher the score (maximum of 132) the more symptomatic the participant. The SAC was a cognitive assessment monitoring Immediate Memory (max score: 5), Concentration (max score: 15), Orientation (max score 5), and Delayed Recall (max score: 5) for a total of 50 points possible when summed together. The lower the score the more affected the memory of the participant. The modified BESS counts total errors (max score: 30) for each 20-sec eye closed conditions: double leg stance, single leg stance (non-dominant), and tandem stance on a firm surface. Lower scores represent better performance.

\section*{Statistical Analysis}

Descriptive statistics were calculated for each of the dependent variables (symptom score, symptom severity, modified BESS, and SAC total). To determine if there were differences across sessions (control, euhydration, dehydrated), a one-way Repeated Measures Analysis of Variance was used for each of the dependent variables. First, assumption testing of linearity, normality, and sphericity were assessed. If a violation in sphericity was found, a Greenhouse-Geisser adjustment was made. For statistically significant results from the RM ANOVA, pairwise post-hoc testing was completed. Data were analyzed using Statistical Package for the Social Sciences (IBM SPSS, Inc., 26.0, Chicago, IL, USA). An alpha level of $\leq 0.05$ was used for all analyses.

\section*{Results}

Descriptive statistics for the four dependent variables can be found in Table 1. There was a statistically significant difference among the sessions for both the SCAT3 symptom severity scores ($F_{2,20}=4.61, p=0.034$) and the SCAT3 symptom total ($F_{2,28}=5.64, p=0.009$). The rested control session had a significantly lower mean symptom severity score (1.56±1.86) than the dehydrated session (6.31±7.78, $p = 0.032$). The rested control session had a significantly lower mean symptom score (1.31±1.45) than the dehydrated session (3.94±3.79, $p = 0.019$). Additionally, the rested control session was significantly lower for symptom total when compared to the euhydrated session (2.18±2.33, $p = 0.019$). No statistically significant differences were seen for modified BESS or SAC total.

\section*{Discussion}

Best practices suggest that health care professionals (athletic trainers [ATs], physical therapists [PTs], and medical doctors [MDs]) examining patients suspected of sustaining a concussion use a multifaceted approach. In order to accurately diagnose a concussion, ATs focus on a number of functions, including reaction time, short- and long-term memory, balance, and self-reported physical symptoms. Deviations in these scores, from baseline, are used to indicate the possibility of a concussion. Zimmer et al\textsuperscript{17} reported that average baseline scores in the SCAT2 were 91.08 ± 5.60 with average number of symptoms reported at 1.75 and the SAC and BESS scores were 27.17±2.10 and 25.64 ± 4.07, respectively. Putukian et al.\textsuperscript{18} indicated significant correlations between SCAT2 scores and various individual patient outcomes with as little as a 3.5-point drop from baseline.

However, there are other conditions that can also result in alterations in these variables that may lead to incorrect diagnosis on the field using commonly used examination tools, like the SCAT3. Previous researchers have reported changes in memory, reaction time, and balance as a result of dehydration\textsuperscript{13,15,19} due to possible reduced neural capacity and negative impact due to reduced blood volume.\textsuperscript{20} Comparatively, the current project resulted in similar variations in symptoms commonly associated with concussions.

\begin{table}[h]
\centering
\caption{SCAT 3 scores stratified across sessions.}
\begin{tabular}{|c|c|c|c|c|}
\hline
 & Control (n=16) & Euhydrated (n=17) & Dehydrated (n=16) & Total (N=49) \\
\hline
Symptom Total & 1.31±1.45 & 2.18±2.33 & 3.94±3.79 & 2.47±2.85 \\
Symptom Severity Total & 1.56±1.86 & 3.24±4.04 & 6.31±7.78 & 3.69±5.41 \\
Memory Total & 28.31±1.25 & 27.71±2.23 & 27.31±2.02 & 27.78±1.90 \\
BESS Total & 2.13±2.42 & 2.88±3.12 & 4.50±2.90 & 3.16±2.95 \\
\hline
\end{tabular}
\end{table}
but not balance or neurocognitive function. The researchers suspect a combination of dehydration and fatigue were the underlying factors that altered the participants’ symptoms as compared to their control levels. Fatigue has previously been found to increase injury risk while decreasing performance. In addition, lower cerebral performance has been linked to an increased risk of non-contact ACL injury perhaps due to loss of central control. The researchers concede that dehydration and/or fatigue can make the SCAT3 more conservative by increasing false-positive diagnoses, but believe this is less concerning compared to false-negative diagnoses where concussed patients would be allowed to inappropriately return to play and risk a variety of complications. In other words, it is more reasonable to hold a patient out of activity if a concussion cannot be ruled out regardless of whether it can be ruled in or not. However, effort should be made to provide the most accurate diagnoses possible during activity to improve clinical care.

**Balance Scores:** Mild exercise-induced dehydration resulted in higher (worse) modified BESS scores (4.50 ± 2.90) compared to control and euhydrated sessions, however, this difference was not statistically significant. Similarly, Patel and colleagues reported no deviation in the BESS scores with dehydration levels greater than those reported in this project (2.50±0.65% vs 1.61±1.0%, respectively). They speculated that a learning effect could have been the reason for the lack of significant differences between the control and experimental groups. It is unlikely a learning effect played a role in the current study due to the randomized order of sessions, indicating that the level of exercise intensity, exercise type, nor the dehydration level were significant enough to illicit an alteration in balance. The change we documented between the control group (2.13 ± 2.42) and the euhydrated group (2.88 ± 3.12) were much smaller than the difference between collegiate aged concussed (5.46 ± 5.44) patients and their baseline test results (5.87 ± 5.99). Others have determined that dehydration alone has not been found to alter BESS scores (full version, not modified) in isolation; however, exercise combined with dehydration did alter BESS scores. It has been suspected that the level of dehydration experienced by the participants in the current study may be similar to those seen in clinical practice on the sidelines, indicating the importance of considering hydration levels during clinical sideline testing, but more testing is needed. Similarly, completing components of the SCAT in a different environment or after fatiguing exercise compared to baseline has also been found to alter test scores. However, resting for 20 minutes after exercise negates the regression in BESS scores. It remains unknown if a rest period with or without fluid access after dehydrating exercise would bring modified BESS scores back to baseline.

**Symptom Scores:** Participants’ self-reported symptom scores and symptom severity scores increased as a result of dehydration following fluid restricted exercise (Figure 1). The observed high standard deviations, similar to previous studies, strengthening the case for obtaining a baseline. A symptom severity increase was observed from the control (1.56 ± 1.86) to the euhydrated condition (3.24 ± 4.04), albeit much smaller when compared to the difference between the dehydrated condition (6.51 ± 7.78), and not likely to be clinically significant. This pattern was also seen for symptom count in the sample with the lowest number of symptoms in the control session (1.31 ± 1.45), then in the euhydrated session (2.18 ± 2.35) and finally the highest number of symptoms in the dehydrated session (3.94 ± 3.79). Previous studies have found elevated headache, feeling in a fog, and feeling slowed down symptom severity scores after dehydration. The reported symptom scores of the dehydrated group do fall within one standard deviation of reported symptom scores of concussed high school and collegiate athletes, indicating that there may a possible relationship between the physiological effects of dehydration and clinical symptoms of a concussion. Symptom severity scores may require multiple baseline measurements or measurements in different climates to improve clinical decisions, especially if more severe climate conditions are present when concussion is suspected, such as extreme heat and humidity which may exacerbate dehydration.

**SAC Total:** The effect of exercise and hydration status for SAC scores was parallel to the findings for balance, with no significant impact on SAC scores. Compared to the control session, the euhydrated sessions only scored an average of 0.6 points worse, compared to the dehydrated sessions 1.00-point degradation. Previous researchers have shown high sensitivity and specificity with a 1.00-point difference between baseline and post-concussion assessments, which may suggest the findings of mean score differences after dehydrating exercise would be less indicative of a concussive event. Similarly, previous authors have shown no difference in SAC scores based on hydration status. In addition, other studies have found the SAC to be resistant to score changes based on the environment. Therefore, the SAC component to the SCAT3 may be more resistant to extraneous variables compared to balance and symptom scores.

**Limitations and Future Directions:** The data was collected from a convenience sample of seventeen recreationally active volunteers with various sport experiences. These participants may or may not respond to exercise similarly to professional, collegiate, or scholastic athletes. It would be interesting to examine athletes from different sports, fitness levels, and levels of acclimatization to heat and/or hu-
midity to determine how dehydration may alter balance, symptoms, and mental status. In addition, the exercise protocol required 60 minutes of steady state running on a treadmill which is an activity uncommon in most sports and shorter than the duration of most athletic practices and games. Future research could determine whether more interval type exercise protocols for a period of time closer to many practices (2 hours) with and without fluid restriction would make more or less of an effect on SCAT3 scores. Finally, monitoring diet would have also brought more insight to the effect of exercise and dehydration on performance in field concussion testing.

CONCLUSION

The present findings indicate that worsened symptom and symptom severity scores occurred in subjects during the fluid restricted exercise condition compared to those exercising with unlimited fluids and a control session, in healthy, non-concussed subjects. As such, clinicians working with athletes and tasked with monitoring and accurately diagnosing head trauma should take factors such as hydration status into account when assessing patients for concussion using the SCAT3. If dehydration is suspected, patients should be provided time to rehydrate if necessary to ensure accurate diagnosis.

CONFLICTS OF INTEREST

No conflicts of interest to report by all authors.

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REFERENCES


Characterization of Injuries in Male and Female Ultimate Frisbee Players at the Elite Club-Level

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Keywords: prevalence, epidemiology, prevention, gender

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Background
Ultimate Frisbee is a rapidly growing sport played in all levels of competition in men’s, women’s, and coed divisions. Despite widespread popularity, there remains a lack of research on injury risk and prevalence during a season.

Purpose
To determine the prevalence of injuries among elite club-level men and women Ultimate Frisbee players and to identify elements associated with injury during a single season.

Study Design
Descriptive epidemiological study.

Methods
Voluntary preseason and postseason online surveys were distributed to local elite club-level Ultimate teams in 2019. Surveys assessed players’ lifetime Ultimate-associated injury history, injury status, training regimen, and other related elements.

Results
Fifty-seven and 84 players were eligible to complete the preseason and postseason surveys, respectively. Prior to the 2019 season, 97% of female respondents and 100% of male respondents reported a previous Ultimate-related injury in their career, with all reporting a prior lower extremity injury. During the 2019 season, 56% of respondents reported being injured, and 12% missed one month or more of the season, with 88% of injured players reporting a lower extremity injury. Men reported more ankle and calf injuries than women, and there was a strong negative correlation between time missed due to injury during the 2018 season and the number of days per week spent weight-training and accumulated training.

Conclusion
There is a high prevalence of lower extremity injury among elite club-level Ultimate players during a single season and pervasive lower extremity injury history may contribute to high injury prevalence. Observed injury patterns suggest targeted interventions including Nordic Hamstring Exercises and balance and proprioceptive training may decrease injury risk. Further research into this topic is needed to help reduce injury in these athletes.

Levels of Evidence
Level 3.
Table 1: Preseason and postseason survey information

<table>
<thead>
<tr>
<th>Preseason Survey Data</th>
<th>Postseason Survey Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Age</td>
<td>• Injury during 2019 season</td>
</tr>
<tr>
<td>• Number of years playing Ultimate</td>
<td>• Time missed due to injury during 2019 season</td>
</tr>
<tr>
<td>• History of Ultimate-related injury</td>
<td>• Number of days/week participating in Ultimate, weight training, and cross-training</td>
</tr>
<tr>
<td>• Time missed due to injury during 2018 season</td>
<td></td>
</tr>
<tr>
<td>• History of Ultimate-related surgery</td>
<td></td>
</tr>
<tr>
<td>• Number of days/week participating in Ultimate, weight training, and cross-training</td>
<td></td>
</tr>
</tbody>
</table>

INTRODUCTION
Ultimate Frisbee, or simply "Ultimate," is a rapidly growing non-contact sport played in all levels of competition in men's, women's, and coed divisions. In 2015, the Olympic Committee officially recognized Ultimate\(^1\), bringing it one step closer to inclusion in the Olympic Games. USA Ultimate reports an estimated seven million Ultimate players across 80 countries.\(^2\) Despite this large player base, there is a lack of research on injury prevalence and risk. In a retrospective analysis of collegiate club sports injuries reported by a local sports clinic, Ultimate athletes had higher injury rates than other non-contact sports and comparable injury rates to rugby athletes.\(^3\) These findings suggest Ultimate athletes are at higher risk of injury, and specific aspects of Ultimate may increase the risk of injury relative to other non-contact sports. Two retrospective studies described injuries incurred in the Ultimate tournament setting,\(^4,5\) but no studies have described injury prevalence or identified injury risk factors during an elite club-level season.

The purpose of this study was to determine the prevalence of injuries among elite club-level men and women Ultimate Frisbee players and to identify elements associated with injury during a single season. This study focused on elite club-level players, which currently represents the highest level of competition in Ultimate.

METHODS
DATA COLLECTION
Preseason and postseason online surveys were designed by a single author to evaluate Ultimate players' demographics, lifetime Ultimate-associated injury/surgical history, current injury status, and other related elements (Table 1). This study was reviewed by the University of Washington Institutional Review Board and designated exempt.

Team captains of the top men's and women's club teams from a single geographic region were contacted to inform players of the nature of this study and their team's voluntary involvement. All members of teams contacted were at least 18 years of age, and each team had 28 players. The women's team had a member added prior to the season, resulting in a total 28 men and 29 women eligible to complete the preseason survey. The preseason online survey was distributed before the start of the 2019 season (May through October). After the completion of the season, which culminates in a national competition, the postseason online survey was distributed. The top coed team from the region was also asked to participate in the postseason survey, resulting in a total 42 men and 42 women eligible to complete the postseason survey.

INJURY STATUS, SITE, AND SEVERITY
Injury status was based on self-reported injuries, and players were considered injured if any injury was reported. Players also reported time missed during the 2018 or 2019 season due to injury (preseason and postseason surveys, respectively) and options included durations of N/A, <1 week, 1 week – 1 month, 1 month – 3 months, and >3 months. In preseason surveys, athletes reported their lifetime Ultimate-associated injury history. In postseason surveys, athletes reported injuries sustained during the 2019 Ultimate season. Injuries were classified into one of three injury regions: upper extremity, lower extremity, and head/neck/trunk. Injuries involving or distal to the hip joint were considered lower extremity injuries, injuries involving or distal to the shoulder joint were considered upper extremity injuries, and injuries to the head, neck, or trunk were categorized as head/neck/trunk injuries. During survey data compilation, players' descriptions of injury were used to verify appropriate categorization into the three injury regions.

TRAINING REGIMEN
Training was categorized into the following categories: Ultimate, cross-training, and weight-training. Players were asked to report the average number of days per week spent doing each type of training in the four weeks prior to completing the preseason and postseason surveys. Players' accumulated training was then determined by the sum of training days per week for all three categories. Ultimate training was defined as days per week of engaging in Ultimate play. Weight-training was defined as days per week engaging in weight training. Cross-training was defined as days per week spent doing any type of training other than playing Ultimate or weight-training.

STATISTICAL ANALYSIS
After the 2019 season, survey results were collected from the online survey host site and compiled in Microsoft Excel 2010. All surveys completed were included for analysis. The sample correlation coefficient (r) was used to determine linear correlations. Independent t-test comparisons were used when comparing means and \(\chi^2\) comparisons were used.
when comparing proportions to determine statistically significant differences, using \( p < 0.05 \) as a threshold for significance.

RESULTS

DEMOGRAPHICS, TRAINING, SURVEY COMPLETION

Of the 57 eligible athletes, 44 (77%) completed the preseason survey. There were no statistical differences when comparing men and women in age (29.4 vs. 28.9, \( t = -0.41, p = 0.67 \)), years of playing Ultimate (11.9 vs. 12.3, \( t = 0.33, p = 0.76 \)), or Ultimate-related surgical history (48% vs. 40%, \( \chi^2 = 0.25, p = 0.62 \)). There were no statistical differences comparing men and women by training regimen (Table 2). Notably, preseason surveys were completed by 29 female players but only 15 male players (100% vs. 54%, \( \chi^2 = 15.5, p = 0.0001 \)).

Postseason surveys were completed by 23 female players and 18 male players (55% vs. 43%, \( \chi^2 = 0.57, p = 0.45 \)). Men reported playing Ultimate more days per week, on average, than women (5.2 vs. 2.4, \( t = -2.05, p = 0.047 \)) in the 4 weeks prior to completing postseason surveys. There were no other statistical differences between men and women regarding other training regimens (Table 2).

PRESEASON INJURY SURVEY

Preseason surveys showed 43 (98%) players reported a previous Ultimate-related injury in their career, and 29 (66%) players had previous Ultimate-related injuries in more than one injury region (Table 3). All players reporting previous Ultimate-related injury had an injury to their lower extremity. The most common injuries reported involved players’ hamstrings (14), ankle (13), ACL (8), shoulder (14), and back (11). Other commonly reported Ultimate-related injuries suffered during a previous season are outlined in Table 4. During the 2018 season, 39 (89%) players missed some time due to injury, with 12 (27%) players missing one month or longer (Table 3).

Women had a higher prevalence of previous foot injuries (31% vs. 0%, \( \chi^2 = 5.7, p = 0.017 \)), while men had a higher prevalence of ankle injuries (47% vs. 17%, \( \chi^2 = 4.4, p = 0.04 \)). There were no other gender differences in previous injury prevalence. A larger proportion of men missed one week or more of the 2018 season due to injury compared to women (73% vs. 31%, \( \chi^2 = 6.9, p = 0.009 \)) (Table 3).

There was a strong negative correlation between amount of time missed due to injury during the 2018 season and days per week spent weight training (\( r = -0.92, p = 0.026 \)) (Figure 1) and accumulated training days (\( r = -0.96, p = 0.01 \)) (Figure 2) in the four weeks prior to players completing the preseason survey. There was a nonsignificant negative correlation between the amount of time missed during the 2018 season and days per week spent playing Ultimate (\( r = -0.69, p = 0.20 \)) and cross-training (\( r = -0.74, p = 0.15 \)) in the four weeks prior to players completing the preseason survey.

POSTSEASON INJURY SURVEY

Postseason surveys showed that 26 (63%) players were injured during the 2019 season, with 23 (56%) reporting a lower extremity injury and 8 (20%) players reporting injuries in more than one injury region. The lower extremity was the most injured region, with hamstring (8), ankle (7), and back (3) injuries being the most common injuries reported. Other commonly reported injuries suffered during the 2019 season are outlined in Table 4. A majority of players (63%) reported missing some time during the season due to injury, and 5 (12%) missed a month or longer (Table 3).

Compared to women, men had a higher prevalence of ankle (53% vs. 4%, \( \chi^2 = 5.9, p = 0.01 \)) and calf (17% vs. 0%, \( \chi^2 = 4.1, p = 0.025 \)) injuries. There were no other differences in injury prevalence by gender. There were no differences in time missed due to injury by gender during the 2019 season (Table 3). There were nonsignificant negative correlations between amount of time missed due to injury during the 2019 season and days per week spent cross-training (\( r = -0.73, p = 0.27 \)), weight training (\( r = -0.28, p = 0.72 \)), and accumulated training days (\( r = -0.53, p = 0.47 \)) in the four weeks prior to players completing the postseason survey. There was a nonsignificant positive correlation between amount of time missed due to injury during the 2019 season and days per week spent playing Ultimate (\( r = 0.91, p = 0.092 \)) in the four weeks prior to completion of the 2019 postseason survey.

### Table 2: Preseason and postseason comparisons by participation in various training programs

<table>
<thead>
<tr>
<th></th>
<th>Preseason</th>
<th></th>
<th></th>
<th></th>
<th>Postseason</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
<td>Women</td>
<td>t-value</td>
<td>p-value</td>
<td>Men</td>
<td>Women</td>
<td>t-value</td>
<td>p-value</td>
</tr>
<tr>
<td>Average days/week playing Ultimate</td>
<td>2.7</td>
<td>2.4</td>
<td>-0.48</td>
<td>0.63</td>
<td>3.2</td>
<td>2.4</td>
<td>-2.05</td>
<td>0.047*</td>
</tr>
<tr>
<td>Average days/week cross-training</td>
<td>4.1</td>
<td>3.4</td>
<td>-0.95</td>
<td>0.35</td>
<td>1.9</td>
<td>2.2</td>
<td>0.69</td>
<td>0.5</td>
</tr>
<tr>
<td>Average days/week weight-training</td>
<td>3.1</td>
<td>2.5</td>
<td>-1.07</td>
<td>0.29</td>
<td>1.2</td>
<td>1.2</td>
<td>-0.01</td>
<td>0.99</td>
</tr>
<tr>
<td>Average accumulated training days</td>
<td>9.9</td>
<td>8.4</td>
<td>-1.1</td>
<td>0.28</td>
<td>6.3</td>
<td>5.8</td>
<td>-0.5</td>
<td>0.62</td>
</tr>
</tbody>
</table>

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Table 3: Injury history (preseason), injury occurrence (postseason), injury region, and time missed compared by sex

<table>
<thead>
<tr>
<th>Preseason</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men (%)</td>
<td>Women (%)</td>
<td>Total (%)</td>
<td>p-value</td>
</tr>
<tr>
<td>History of Ultimate-related injury</td>
<td>15/15 (100)</td>
<td>28/29 (97)</td>
<td>43/44 (98)</td>
<td>0.47</td>
</tr>
<tr>
<td>Lower Extremity</td>
<td>15/15 (100)</td>
<td>28/29 (97)</td>
<td>43/44 (98)</td>
<td>0.47</td>
</tr>
<tr>
<td>Upper Extremity</td>
<td>9/15 (60)</td>
<td>12/29 (41)</td>
<td>21/44 (48)</td>
<td>0.25</td>
</tr>
<tr>
<td>Head/Neck/Trunk</td>
<td>4/15 (27)</td>
<td>10/29 (34)</td>
<td>14/44 (32)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Time missed during 2018 season:

<table>
<thead>
<tr>
<th></th>
<th>Men (%)</th>
<th>Women (%)</th>
<th>Total (%)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>0/15 (0)</td>
<td>5/29 (17)</td>
<td>5/44 (11)</td>
<td>0.09</td>
</tr>
<tr>
<td>&lt;1 wk</td>
<td>4/15 (27)</td>
<td>15/29 (52)</td>
<td>19/44 (43)</td>
<td>0.12</td>
</tr>
<tr>
<td>1 wk – 1 mo</td>
<td>5/15 (33)</td>
<td>3/29 (10)</td>
<td>8/44 (18)</td>
<td>0.06</td>
</tr>
<tr>
<td>&gt;3 mo</td>
<td>1/15 (7)</td>
<td>2/29 (7)</td>
<td>3/44 (7)</td>
<td>0.98</td>
</tr>
<tr>
<td>season</td>
<td>0/15 (0)</td>
<td>1/29 (3)</td>
<td>1/44 (2)</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Postseason

<table>
<thead>
<tr>
<th></th>
<th>Men (%)</th>
<th>Women (%)</th>
<th>Total (%)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injured during 2019 season</td>
<td>13/18 (72)</td>
<td>13/23 (57)</td>
<td>26/41 (63)</td>
<td>0.32</td>
</tr>
<tr>
<td>Lower Extremity</td>
<td>11/18 (61)</td>
<td>12/23 (52)</td>
<td>23/41 (56)</td>
<td>0.58</td>
</tr>
<tr>
<td>Upper Extremity</td>
<td>1/18 (6)</td>
<td>4/23 (17)</td>
<td>5/41 (12)</td>
<td>0.28</td>
</tr>
<tr>
<td>Head/Neck/Trunk</td>
<td>4/18 (22)</td>
<td>4/23 (17)</td>
<td>8/41 (20)</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Time missed during 2019 season:

<table>
<thead>
<tr>
<th></th>
<th>Men (%)</th>
<th>Women (%)</th>
<th>Total (%)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>6/18 (33)</td>
<td>9/23 (39)</td>
<td>15/41 (37)</td>
<td>0.71</td>
</tr>
<tr>
<td>&lt;1 wk</td>
<td>4/18 (22)</td>
<td>5/23 (22)</td>
<td>9/41 (22)</td>
<td>0.97</td>
</tr>
<tr>
<td>1 wk – 1 mo</td>
<td>5/18 (28)</td>
<td>7/23 (30)</td>
<td>12/41 (29)</td>
<td>0.86</td>
</tr>
<tr>
<td>&gt;3 mo</td>
<td>3/18 (17)</td>
<td>2/23 (9)</td>
<td>5/41 (12)</td>
<td>0.44</td>
</tr>
<tr>
<td>season</td>
<td>0/18 (0)</td>
<td>0/23 (0)</td>
<td>0/41 (0)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4: Number and commonly reported injuries by injury region, (n=44 preseason, n=41 postseason)

<table>
<thead>
<tr>
<th>Preseason Injury Survey – Lifetime History of Ultimate-related Injurya</th>
<th>Total</th>
<th>Commonly Reported Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Extremity</td>
<td>43</td>
<td>Hamstring strain (14), ankle sprain (13), ACL tear (8)</td>
</tr>
<tr>
<td>Upper Extremity</td>
<td>21</td>
<td>Shoulder/rotator cuff injury (9), shoulder/AC dislocation (5)</td>
</tr>
<tr>
<td>Head/Neck/Trunk</td>
<td>14</td>
<td>Middle/lower back pain (11), concussion (1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Postseason Injury Survey – Injury During 2019 Seasona</th>
<th>Total</th>
<th>Commonly Reported Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Extremity</td>
<td>23</td>
<td>Hamstring strain (8), ankle sprain (7)</td>
</tr>
<tr>
<td>Upper Extremity</td>
<td>5</td>
<td>Shoulder/rotator cuff injury (1), shoulder impingement (1), lateral epicondylitis (1)</td>
</tr>
<tr>
<td>Head/Neck/Trunk</td>
<td>7</td>
<td>Middle back pain (3), concussion (1)</td>
</tr>
</tbody>
</table>
DISCUSSION

There was a high injury prevalence in the 2019 season, with 13 (57%) women and 15 (72%) men reporting injuries sustained during the season. Additionally, nearly all preseason respondents reported a history of injury while playing Ultimate, with 28 (97%) women and 15 (100%) men suffering a previous Ultimate-related injury. All 43 players reporting a lifetime history of Ultimate-related injury reported a previous lower extremity injury. As seen in other studies on Ultimate injuries, lower extremity injuries made up a large proportion of injuries during the 2019 season, with 12 (92%) injured women and 11 (85%) injured men reporting a lower extremity injury.

Thigh injuries were common in both men and women, largely represented by hamstring injury. Given the high hamstring injury prevalence, more emphasis should be placed on hamstring injury prevention. Incorporating Nordic Hamstring Exercises (NHE) in both amateur and professional soccer players’ training regimen has been shown to reduce hamstring injury incidence. Given soccer and Ultimate players’ similar in-game activity patterns like sprinting and cutting, the benefits seen in soccer players from NHE may translate to Ultimate players. FIFA 11+ is a warmup program originally designed for injury prevention for soccer players that was subsequently found to reduce injury when implemented by elite male basketball players. Similar to FIFA 11+’s success in basketball players, NHE’s protective factors may translate to Ultimate players when incorporated into warmup and training regimens as a way to reduce injury prevalence.
potential risk reduction tool.

Noteworthy differences in injury prevalence when comparing genders were men sustaining more ankle (33% vs. 4%, \( \chi^2 = 5.9, p = 0.01 \)) injuries than women. The high prevalence of ankle injuries in male Ultimate players suggests they may benefit from increased balance and proprioceptive training.\(^{12-17}\) Multiple studies have shown balance and proprioceptive training decreased the incidence and recurrence of ankle injuries in multiple sport populations, including soccer, basketball, and football, and this benefit may also translate to Ultimate players. Another factor that may be contributing to the high prevalence of lower extremity injury is the extensive history of previous lower extremity injury. Previous lower extremity injury has been shown to be an intrinsic risk factor for calf and hamstring injuries.\(^{18-20}\) Preseason survey results show 28 (97%) women and 15 (100%) men had a previous lower extremity injury, identifying this population as one that is implicitly at increased risk of calf and hamstring injury, and potentially contributing to the high lower extremity injury prevalence.

Due to field and player availability, Ultimate players frequently train for extended periods on weekend back-to-back days. Additionally, players may see a sudden increase in play during weekend tournaments where they routinely have three to four games per day. Currently, it is unclear what effect, if any, this erratic pattern of training and competition has on players' injury risk. Chronic workload is defined as the average workload over a four-week span\(^{21}\) and previous studies have shown that both weight training\(^{22,23}\) and increased chronic workload\(^{24,25}\) have a protective effect on injury risk. In preseason and postseason surveys, chronic workload was approximated by calculating players' average accumulated training in the 4 weeks prior to completing a survey. Preseason survey results showed a strong negative correlation between time missed due to injury during the 2018 season and both players' reported weight training days per week \( (r = -0.92, p = 0.026) \) and accumulated training \( (r = -0.96, p = 0.01) \). These results suggest that players who reported more weight training days per week and more accumulated training days missed less time due to injury. While this is consistent with previous studies demonstrating the protective effects of weight training and increased chronic workload, the interpretation of this observed correlation is unclear due to several limitations. The use of players' reported training regimen as approximations of their weight training or chronic workload is non-validated. Other limitations, including training duration and intensities being unstandardized and training days per week being self-reported by players, make it unclear how accurately reported training regimens represent a player's weight training or chronic workload prior to injury. Furthermore, postseason survey results did not redemonstrate this negative correlation, warranting cautious interpretation of this association. Nonetheless, these findings identify athlete workload monitoring as an important area of research to understand the relationship between the unique training and competition patterns of Ultimate athletes and injury risk.

Preseason surveys revealed that only one (2%) player reported a history of concussion while playing Ultimate, and postseason surveys found only one (2%) concussion reported during the 2019 season, in contrast to a previous study reporting 26% of players acknowledged a concussion while playing Ultimate.\(^{26}\) One possible contributing factor to the lower number of concussions in the current study is the under-reporting of concussions. The previous study\(^{22}\) found only 80% of players believed they could recognize when they or a teammate sustained a concussion, indicating there is likely a subset of players who may incorrectly report not suffering a concussion. Additionally, the small sample size in this study may underestimate the true prevalence of concussion in Ultimate players.

LIMITATIONS

This study used an online, voluntary survey and is implicitly limited by reporting bias. Additionally, low survey completion rates, particularly in the preseason male and postseason survey populations, limit the strength of study findings. Preseason and postseason survey results were not directly compared for reasons of limiting recall bias, different question sets between surveys, and different subject groups completing the respective surveys due to the addition of the 3rd local coed Ultimate team to the postseason survey group. The accuracy of some survey responses was another limitation. Injury classification was based on self-reported descriptions by players, without verification by a medical professional, making the accuracy of reported injuries unclear. Finally, the interpretation of players' training regimen and its relation to injury risk is uncertain due to several limitations. Days per week spent training was self-reported by players without standardization of intensity or duration necessary to qualify as a "day" of training, limiting conclusions that can be extrapolated by players' training regimens. Furthermore, due to this study's design, players' in-season training regimens prior to injury cannot be confidently determined, precluding a causal relationship between training regimen and injury. Lastly, the clinical significance of the observed correlation between time missed due to injury and training regimen in preseason results is unclear due to reasons previously described and warrants cautious interpretation. Despite these limitations, this is the first study to evaluate the prevalence of injury during an Ultimate season for both elite club-level men and women players and association with possible elements that may contribute to injury in this rapidly growing sport.

CONCLUSION

The results of the current study indicate that there was a high prevalence of self-reported injury among elite club-level male and female Ultimate athletes during the 2019 season, with 88% of injured players reporting a lower extremity injury. Hamstring and ankle injuries were the most commonly reported lower extremity injuries, and men reported more injuries involving the ankle and calf than women. The high prevalence of hamstring and ankle injuries suggest that club-level Ultimate athletes may benefit from targeted interventions, including Nordic Hamstring Exercises, focused warm-up, and balance and proprioceptive training to decrease injury risk. Further research into injury in Ultimate players is needed to help reduce injury in...
these athletes.

STATEMENT OF FINANCIAL DISCLOSURE AND CONFLICT OF INTEREST

The authors have no financial disclosures or conflicts of interest.


International Journal of Sports Physical Therapy


Background and Purpose
Scapular muscle detachment is a rare orthopedic problem that has been described in the literature in patients following traumatic events involving traction, direct trauma, or a motor vehicle accident. The purpose of this case report is to describe the post-operative rehabilitation following scapular muscle reattachment surgery. Unique to this case report is the patient’s perspective, an orthopedic physical therapist with 25 years of experience.

Case Description
A 47-year-old female physical therapist experienced a traction injury to bilateral upper extremities during a medical procedure resulting in bilateral rhomboid, and bilateral lower trapezius muscles were detached from the medial scapular border. Reconstruction of the left scapulothoracic musculature occurred five and one-half years post-injury with the right repaired one year later. This case report describes the rehabilitation program that took one-year to recover for each arm with a period of protected motion for 16-weeks and gradual return to function as a manual physical therapist over a period of one-year.

Outcomes
The American Shoulder and Elbow Surgeons (ASES) Standardized Assessment Form and pain-free range of motion was used pre- and postoperatively. Left and right shoulder pre-operative ASES scores were 68 and 72, respectively. At the one-year post-operative the left shoulder was rated at 82 and the right shoulder was 90. Pain-free range of motion was achieved in both arms by one year. Functional limitations requiring strength overhead were the slowest to return and were not completely back at one year following either surgery.

Discussion
Rehabilitation protocols for scapular muscle reattachment surgery are not commonly available to allow physical therapists to guide their patients and structure a rehabilitation program. This case report provides a sample pre-operative set of educational guidelines and a post-operative protocol for use after scapular reattachment surgery. This case report is unique because it offers a patient perspective who is a physical therapist and underwent this surgery twice. Therefore, providing insight on how to prepare for such a unique operation. The slow recovery is due to three issues 1) the prolonged time from injury to diagnosis created significant muscle wasting and muscular imbalance of surrounding tissues, 2) once this tissue was repaired it requires months of protection to recover, 3) the involved scapulothoracic muscle have to regain adequate strength as the foundation for upper extremity functions.

Level of evidence
Level 5
BACKGROUND

Abnormal scapular position or movement, called scapular dyskinesis, is commonly seen in patients with shoulder injury or pain.1–7 There are multiple causes of scapular dyskinesis including bony (e.g. fracture), neurologic (e.g. long thoracic or accessory nerve palsy), and muscular dysfunction (e.g. soft tissue inflexibility, muscle weakness, inhibition, or imbalance).1,3,8–10 The majority of scapular dyskinesis seen by the therapist is the result of muscular imbalances. Treatments directed at restoring muscular length, strength, and motor control are effective when applying good clinical reasoning to the biomechanics of the upper quadrant.1–6,10–13 However, there is a subset of patients presenting with scapular dyskinesis, that have chronic pain and have not responded to logical and appropriate rehabilitation that have been found to have a periscapular muscular detachment.3 Patients with a scapular muscle detachment can obtain pain reduction and functional improvement by surgically reattaching the muscles first, then rehabilitation.3 To date, there is little information regarding the post-surgical rehabilitation of periscapular muscle tears in the literature.

This case report provides guidelines and insight for rehabilitation after surgical scapular muscle reattachment as well as how this rehabilitation program differs from the more typical rotator cuff repair, which also involves reattachment of the musculotendinous structures. The purpose of this case report is to describe the post-operative rehabilitation following scapular muscle reattachment surgery. This case report is unique as an experienced physical therapist underwent the surgical procedures and was able to provide a perspective of rehabilitation from the combined patient and physical therapist perspective. The subject of the study has been informed that the data and photos taken would be submitted for publication and has given consent.

CASE DESCRIPTION

A 47-year-old female physical therapist sustained a traction injury to bilateral scapulothoracic muscles during a medical procedure. The mechanism of injury occurred while the subject was awaiting anesthetia in the operating room. Both upper extremities were strapped and restrained on a board with the left arm abducted at 100° and the right arm abducted at 80° with elbows extended. A nurse grabbed both ankles and pulled forcefully to move the subject down to the end of the gurney causing a bilateral traction event to the scapulothoracic musculature. The subject recalled immediately feeling a sharp pain with severe burning in bilateral periscapular musculature. Soon after notifying the surgical staff, anesthesia was administered, and the intended procedure performed. Upon awakening from anesthesia, the subject reported significant pain in the periscapular region, neck, left arm and difficulty breathing. These symptoms were attributed to a pneumothorax, confirmed by radiographs, and the patient was immediately returned to surgery for insertion of a chest tube and discharged to home that same day with chest tube removed thirteen days later and return to work as a physical therapist two days after insertion of the chest tube.

From the initial incident, symptoms of periscapular muscle burning, rib pain, cervical pain, and increasing weakness with arm motions overhead and away from the body persisted. Conservative physical therapy interventions along with self-management consisted of rib mobilizations, scapular taping, wearing a postural support shirt, ultrasound to the glenohumeral joint, anti-inflammatory medications, and modalities such as ice and heat daily. Strengthening exercise consisted of machine exercises in the gym (such as leg press, abdominal crunches, latissimus pull downs, shoulder press, chest press, triceps and biceps), light free weights and elastic resistance exercises for the upper extremities including specific scapular exercises for abduction, depression, and elevation. Treadmill and bicycle exercises were incorporated to replace running for cardiovascular fitness. These activities were continued for approximately four years.

Despite consistent interventions there was a significant and progressive decrease in strength and range of motion in both shoulders along with an increase in periscapular, cervical, and shoulder pain. Pre-injury fitness activities including running or bicycling had to be eliminated secondary to increased bilateral shoulder and arm pain. The shoulder pain and periscapular burning disrupted sleep every two to three hours. The subject, as a therapist, felt as though she failed at doing what she commonly instructed her patients to perform daily. And, assuming that there was no frank nerve injury, that it had to be a motor control or muscle length – muscle strength balancing problem; thus, within her skill set to resolve. The dosage of exercises, repetitions, or weights were continually modified to make improvements.

Symptoms persisted and increased from local burning along the medial aspect of the scapula to constant left acromioclavicular joint pain, radiating pain down the left upper extremity to 4th and 5th digits, posterior shoulder pain bilaterally with a "cramping" sensation on the bilateral posterior lateral scapula, cervical pain, headaches, and a sensation of arm feeling very heavy that needed to be supported to mitigate symptoms. The subject’s job as a physical therapist was compromised requiring constant modifications of her body mechanics due to the inability to lift, carry, push or pull the weight of her own extremity, or that of her patient’s. The only relief of symptoms was found in sitting with the medial scapular borders compressed onto the trunk with the back of a firm chair and the left upper extremity supported in abduction and slight external rotation. This maneuver of manual compression the scapula onto the trunk for stability mimics the "scapular stabilization" test performed in the clinic. Obtaining such significant and immediate relief confirmed to the therapist/subject that the primary cause of the problem has to do with the lack of scapular stability.

Four years after the initial injury, the subject sought an orthopedic consult secondary to constant left acromioclavicular joint (ACJ) pain and increasing difficulty with all functional activities. An injection to the left ACJ provided immediate relief for a couple days and diminished to 50% in the AC for two weeks but no meaningful change in symptoms to the rest of the shoulder or arm. A subsequent
arthrogram revealed a tear in the upper labrum which involved the biceps tendon anchor. The arthrogram was negative for posterior labral tear and rotator cuff tear. A bicipital tenodesis was proposed but declined by the subject.

Electrodiagnostic testing was ordered to rule out nerve injury. There was no electromyographic evidence of cervical radiculopathy, plexopathy, dorsal scapular neuropathy, long thoracic nerve palsy, spinal accessory neuropathy or peripheral neuropathy on the left musculature. All nerve conduction velocities for median and ulnar nerves were greater than 53 m/s ruling out peripheral neuropathy. Antidromic sensory nerve conduction velocities were 36-38m/s for radial, ulnar, and median nerves which are within normal values for sensory nerve testing. Innervation to the muscles were intact yet strengthening and motor control exercises were not effective and injections into the joint provided no relief. The subject suspected a scapular muscle detachment as a possible cause of the chronic symptoms. The subject sought out another orthopedic surgeon who specializes in scapular muscle dysfunction.

SCAPULAR SURGEON CLINICAL EXAMINATION

A thorough clinical examination was carried out by the orthopedic surgeon. (Table 1) The clinical examination revealed that there was significant scapular muscle involvement. Based on the failure of injections, rehabilitation, negative EMG, and the duration of symptoms the clinical examination was consistent with a diagnosis of scapular muscle detachment injury bilaterally.\(^3\) Surgery for reattachment of the left scapular muscles, which were more involved was discussed with the subject, along with the post-operative rehabilitation limitations. The patient consented and was scheduled for surgery 5.5 years from initial injury. This time frame for diagnosis and relevant surgery is consistent with reported literature of an average of four years.\(^3\) The right scapula musculature was repaired approximately one year later.

SCAPULAR MUSCLE REPAIR SURGERY

The goals of scapular muscle repair surgery are to determine the extent of the muscle damage to the periscapular muscles, identify and mobilize the damaged tissue, and re-establish normal attachment of the muscles to the bone. For this subject, the left scapula required reattachment of the middle and lower trapezius and the rhomboid major muscles. The right scapular muscle reattachment was performed 11 months after the left shoulder. This surgery required reattachment of the lower trapezius, rhomboid major and minor. Detailed description of this surgical procedure has been previously described.\(^3\)

POST OPERATIVE REHABILITATION

Post-operative management of scapular muscle reattachment is outlined in a protocol available at the Lexington Clinic website: https://www.lexingtonclinic.com/assets/files/Documents/2018%20LC%20Orthopedics%20Scapular%20Muscle%20Reattachment%202.pdf (Copy and paste the link into your web browser to access the protocol) These guidelines are modified for each patient based on the surgeon’s assessment of tissue quality, size of tear, and individual patient’s health. A significant modification that is not described in the Lexington Clinic program relates to pre-operative education. As this subject underwent the surgery twice, development of a pre-operative program made recovery much easier following the second surgery. Pre-operative treatments help the patient prepare for activities of daily living (ADL's) in the first six weeks when no formal therapy is prescribed and lessens the chance of damaging the healing tissues. (Appendix A) The rehabilitation program that was carried out for this subject follows the four-phase program described above in the protocol from the Lexington Clinic. Specific treatments are detailed below and in Appendix B to explain how the goals were achieved.
Table 1: Scapular surgeon’s clinical examination

<table>
<thead>
<tr>
<th>Observation</th>
<th>Static scapular position: excessive scapular internal rotation causing winging of the medial border and protraction bilaterally (Figure 1). Dynamic scapular mobility: positive scapular dyskinesis during active elevation in all planes of motion.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palpation</td>
<td>A palpable divot was evident along the superior medial border of the scapula where the subject described the “burning” sensations on both scapulae (L&gt;R). Palpation was performed by lightly sliding his hand along the medial border of the scapula from superior to inferior. This was a different technique than previously performed by other surgeons where the palpation was only a deep pressure applied by the thumb from posterior to anterior. Tenderness and increased tone were noted in the pectoralis minor, infraspinatus, latissimus dorsi, teres major and minor muscles bilaterally.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range of Motion</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation with scapular dyskinesis</td>
<td>100°</td>
<td>120°</td>
</tr>
<tr>
<td>Hand Behind Back</td>
<td>T6</td>
<td>T10</td>
</tr>
<tr>
<td>Active External Rotation at side</td>
<td>30°</td>
<td>45°</td>
</tr>
<tr>
<td>Passive External Rotation at side</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>Active External Rotation at 90°*</td>
<td>45°</td>
<td>45°</td>
</tr>
</tbody>
</table>

*Limited by weakness not by pain

<table>
<thead>
<tr>
<th>Special Tests</th>
<th>Scapular reposition test: Positive bilaterally; indicating that scapular stability is key for rehab and lack of the stability contributes to the cause of the symptoms. Scapular assistance tests: Positive bilaterally; indicating that proper scapular motion is needed for symptom resolution.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>Manual muscle testing was performed manually using the grading system described by Kendall. Both shoulders were painful with inability to obtain or maintain scapular neutral on either extremity. A muscle contraction was palpable along the medial attachment at the thoracic spine with attempts at scapular adduction and depression. Upper extremity weight bearing demonstrated increased bilateral scapular winging, abduction, and upward rotation as the antagonistic rhomboid musculature was not engaged. (Figure 2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pre-operative</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhomboids</td>
<td>1+/5</td>
<td>2-/5</td>
</tr>
<tr>
<td>Middle Trapezius</td>
<td>1+/5</td>
<td>2-/5</td>
</tr>
<tr>
<td>Lower Trapezius</td>
<td>1+/5</td>
<td>2-/5</td>
</tr>
<tr>
<td>Serratus Anterior with protraction</td>
<td>4/5</td>
<td>4/5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outcomes</th>
<th>The patient completed the American Shoulder and Elbow Surgeons (ASES) patient reported function and pain scale pre-operatively and at subsequent follow up time points. The scale is based on 50% level of current pain and 50% on level of perceived function with 100 points indicating no pain and normal function of the upper extremity. The American Shoulder and Elbow Surgeon’s Score for left and right shoulders. The left was operated 1 year prior to the right.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left Pain Score</td>
</tr>
<tr>
<td>Pre-operative</td>
<td>30</td>
</tr>
<tr>
<td>3 months</td>
<td>35</td>
</tr>
<tr>
<td>6 months</td>
<td>40</td>
</tr>
<tr>
<td>12 months</td>
<td>40</td>
</tr>
</tbody>
</table>

One critical difference that physical therapist must keep in mind is that rehabilitation of scapular muscle detachment is slower and has different precautions than the more common rehabilitation after a rotator cuff repair. With a rotator cuff repair, retraining the scapular muscles for stability is relatively easy in the first few weeks after surgery, and
helps to restore normal kinematics while the repaired cuff is healing. However, for scapular reattachment surgery, the rhomboids and trapezius muscles that have been surgically reattached need to heal before retraining. Therefore, motions that cause scapular protraction or depression are contraindicated as they place tension on the repair. Because scapular stability is necessary prior to glenohumeral motion, the expectations for acquiring functional arm range of motion differ greatly between the two post-operative groups. In patients with a rotator cuff repair, passive elevation to $90^\circ$ would be expected to be obtained by six weeks and nearly full passive motion re-established by 12 weeks.\textsuperscript{16} Generally, and as in this case report, with scapular muscle reattachment, the goal was passive elevation to $90^\circ$ at 12-16 weeks with good scapular control. That is nearly double the time frames compared to a rotator cuff repair. At four- and five-months post-operatively, passive elevation would approach $120^\circ$ and $160^\circ$, respectively with active range of motion trailing by approximately $20^\circ$. Full passive elevation with ease was not obtained until at least six months post-surgery and full active elevation along with strength recovery took approximately one year in this case.

REHABILITATION PROGRAM SUMMARY

Please refer to Appendix B that outline treatment goals, precautions, therapeutic activities allowed, symptoms associated with recovery, and manual therapy suggestions which serves as supplemental to the explicit Lexington Clinic protocol.

PHASE 1: (0-6 WEEKS)

The pre-operative patient education sessions are most helpful during this phase. The pre-operative sessions serve to help the patient perform simple ADLs such as dressing, don and doff sling, and sleeping positions. It also teaches the patient what types of activities the uninvolved extremity performs that will increase stress to the surgical side and may be harmful to the healing tissues.

PHASE 2: (6-8 WEEKS)

The second phase is when supervised physical therapy begins. However, after a period of immobilization and a surgical intervention preceded by multiple years of muscle imbalance affecting the scapulothoracic joint, obtaining a neutral position of the scapula on the rib cage can be challenging. A cascade of events contributes to difficulty in obtaining a scapular neutral position. First, the unattached muscles are overpowered by healthy antagonist muscles, (i.e., serratus anterior, latissimus dorsi, teres major, pectoralis minor and major muscles) which have been functioning unopposed and compensating to provide stability for several years. Additionally, the surgical trauma affecting infraspinatus followed by six weeks of immobilization decreases the fascial and muscle extensibility. When the humerus moves away from the body, such as with passive range of motion, the lack of infraspinatus muscle flexibility causes the scapula to be pulled laterally or into protraction placing tension on the repair. Therefore, restoration of normal muscle length and fascial mobility is necessary to restore the normal kinematics, with the scapula in neutral. Techniques unique to this case and found beneficial in the early phases of rehabilitation are described below and in Appendix B.

STRETCHING AND SOFT TISSUE INTERVENTIONS

The following three manual techniques were found to be effective in the clinic and progressed as a home program as subject tolerated.

1. Scapulothoracic neutral: With the patient lying on the uninvolved side the treating therapist can passively move the scapula into neutral with retraction and elevation. The therapist stands in front of the patient and places one hand on the scapula with the other over the anterior shoulder and acromioclavicular joint taking care to support the forearm to prevent rotation. The therapist passively moves the scapula through a small arc posteriorly into retraction, with slight elevation, and downwardly rotates the scapula so that the medial border of the scapula is parallel to the thoracic spine. Retraction can be obtained if the therapist aims the medial superior angle of the scapula back and up toward C7-T1. The therapist passively applies downward rotation to the scapula so the medial border is parallel to the thoracic spine. Note, downward rotation is not depression of the scapula. Avoid depression of the scapula which creates tension on the rhomboids and should be avoided it tissue is involved. In the clinic, the therapist can facilitate scapular external rotation by manually stabilizing the medial border of the scapula against the rib cage. (Figure 3) Note, the therapist cannot force this motion but merely directs it and waits until the body essentially “invites them in”. This should be repeated four to six times until the scapula moves passively into retraction with little resistance. Although the position may follow a PNF direction, only the passive retraction – elevation portion is used.\textsuperscript{17} Traditional PNF techniques with a quick stretch into end ranges are not appropriate at this stage to protect the repair.

2. Side lying soft tissue massage: Once the scapula is retracted passively into a neutral position in side-lying, the therapist stabilizes the scapula to protect the repair and performs gentle soft tissue mobilization to the superficial layers of the infraspinatus, posterior deltoid, and proximal triceps. Mobilizing these posterior scapulohumeral muscles
and fascia will allow the initial 20-30° of humeral elevation in the frontal plane during this phase of rehabilitation. (Figure 4)

3. **Pectoralis muscle stretching:** Tight and shorten pectoralis muscles causes scapular anterior tilt and protraction. Therefore, increasing muscle length is a prerequisite for posterior tilt and retraction to obtain scapular neutral. The subject is in a supine position to stabilize the scapula on the table while the therapist applies gentle posterior pressure over the anterior-superior aspect acromion toward posterior tilt with the humerus in neutral rotation, 30° of abduction, and 0-10° of flexion. In hook lying the patient crosses their leg and rotates the lower extremity away from the opposite side and takes slow deep breaths to relax and stretch the pectoral muscles. (Figure 5) The patient should feel the muscle stretch along the muscle belly and not at the anterior humeral head or AC joint. Each stretching technique should be performed gently and slowly for 5-8 repetitions, holding each for 20-60 seconds and repeated 2-3 times a day.

**STRENGTHENING INTERVENTIONS**

1. **Scapular retraction isometrics:** Isolated sub-maximal muscle activity is necessary for normal shoulder kinematics and serves as the basis for progression of neuromotor control once scapular neutral position is obtained. Surface electromyography (EMG) is an excellent tool to train the patient for proprioception and helps to teach submaximal versus a hard, co-contracted muscle contraction. It may take several minutes to learn neuromuscular control of scapular retraction.

2. **Low Row Exercise:** Low row exercise incorporates the kinetic chain and is performed by placing the hands along the edge of a table and taking a step forward with the contralateral lower extremity. Performing a low row exercise properly was difficult for this patient. This patient reported pain and "cramping" along the posterior lateral scapula near the axilla during the low row exercise and reproduced pre-surgical symptoms. This was attributed to traction stress on the repair from scapular protraction rather than retraction during the activity and facilitation of the latissimus dorsi rather than rhomboids. It is critical while instructing this exercise that the patient can perform scapular retraction initially and prior to the step through action.

3. **Opposite Arm Exercise:** Since low row was not tolerated, this subject used the concept of cross-education and irradiation. Resisted bands for pushing and pulling exercises using the uninvolved extremity through the legs and trunk to incorporate the entire kinetic chain were used to indirectly strengthen the scapular retractors even while wearing the brace. Specific repetitions were not used but the subject stopped when fatigue indicated by the presence of the familiar periscapular burning. Fatigue occurred quickly initially requiring frequent rests. Performing the activities more frequently with few repetitions is recommended rather than aiming toward a higher number despite the pain. In this subject, symptom resolved within 5-20 minutes using ice and external support.

4. **Endurance training:** Without the support of the brace, the weight of the extremity pulls the arm down with the scapula going into protraction and depression. One way to gradually wean from the brace is to remove the hand and forearm support from the sling but leave the abductor support strapped around the trunk to allow functional activities with the distal arm at waist level until fatigue symptoms present again. Loosening the anterior strap on the support bolster decreases the percentage of support under the elbow and is easily modified. Tolerance for increased amount of time without support improves gradually. External support for the extremity on a stable or with a pillow allows for functional use of the hand and wrist without the demands of the arm weight.

**PHASE 3: (8-10 WEEKS)**

The emphasis is on good mechanics for passive motion in additional planes. Maximal elevation ranges remain limited to 90°.
**STRETCHING AND SOFT TISSUE INTERVENTIONS**

1. **Side-lying pectoralis minor stretch:** Once the shoulder can reach 70° abduction the patient can perform self pectoralis stretching in side-lying using the uninvolved arm to assist with raising the involved extremity up toward the ceiling. Side-lying on a couch with the trunk against the back of the couch provides the scapula and extremity additional support and relieves the scapular muscle "cramping" sensation. *(Figure 6)*

   A key component for this self-stretch is to assure the scapula is fully retracted and parallel to the spine. The therapist can facilitate this position is by placing one hand along the posterior scapula with their fingers on the patient’s thoracic spine for feedback and passively raise the arm into abduction with the elbow extended. Allow gravity and the weight of the arm to push the scapula into retraction next to the spine. A second maneuver to facilitate scapular retraction is for the therapist to apply a gentle axial compression force through the wrist for gentle contract (into isometric protraction) and relax (into retraction). With the scapula fully retracted, add slight humeral extension to help posteriorly tilt the scapula followed by elevation for pectoralis minor stretch. If there is pain in the anterior shoulder joint rather than the muscle belly, then the scapula is not fully retracted. Cue the patient to gently shrug or rotate the scapula posteriorly to "adjust it". This stretch exercise should be performed 2-3x/day and held for one to two minutes. It may be performed longer or more frequently and is incorporated prior to the strengthening and motor control activities below.

**STRENGTHENING INTERVENTIONS**

1. **Small isolated active internal and external rotation:** Isolated humeral rotation while in a closed kinetic chain environment decreases co-contraction. With the scapula retracted to neutral and the hand resting softly on a table, cue the patient to gently swing the elbow for full humeral external and internal rotation. Alternatively, slight weight bearing through the extremity next to the hips in sitting facilitates the scapular stabilizers and makes separating the two motions (scapular stability and humeral rotation) easier. Early stages of rehabilitation for strengthening the scapular muscles focuses on neuromotor control to improve proprioception and normalize resting posture.10,23 The patient should be cued to initiate all passive and active arm motion with the scapular retractor to promote proximal stabilization and train proper scapular mechanics.20 Arm abduction exercises are progressed from towel slides and ball rolls to wall slides, so the weight of the arm is supported.

2. **Closed kinetic chain weight bearing:** Standing with the arms on a table or counter and leaning on them to facilitate scapular retraction can be progressed by shifting weight from side to side. A scale under the arm is a good way to measure tolerable loads and monitor progression of strengthening.24 Weight bearing progression can be progressed from two arms to one arm and from standing leaning on a table to prone and quadruped positions adding more support requirements by lifting the opposite extremity or a lower extremity.

**PHASE 4: (10-14 WEEKS);**

1. **Endurance assistance:** Endurance of the scapular muscle to hold the weight of the arm out of the sling improves from minutes to hours during this phase and symptoms of fatigue are easily relieved with less than full support. A pillow or arm resting onto a table will suffice for extremity support. A novel, yet effective technique to be able to offload the weight of the extremity yet allow mobility while walking is to place a small (6”) piece of “pool noodle” or towel high under the armpit *(Figure 7).* It can be held in place with an elastic band through the center of the noodle and around the chest. This serves as a convenient way to wean out of the sling yet give some graded support to the extremity without limiting hand and elbow functions for driving and prolonged walking or working.

15+ WEEKS POST-OPERATIVE

The Lexington Clinic protocol does not go beyond 14 weeks, but the general guidelines were applied for this subject. Restoration of full glenohumeral rotation mobility without increasing passive stretch on the scapulothoracic joint remained a challenge for up to 6 months. The frequency of one-on-one physical therapy sessions decreased, and subject responsibility increased as the range progressed. In general, the subject was seen 2x/week from post-op week 6-10 and decreased to weekly for post-operative weeks 11-16. After four months, seeing the subject every 2-3 weeks for progression of the home program and less frequently from 16-24 weeks would be reasonable. At six months post-operative the subject should have nearly full passive range of motion. Formal visits were dependent on the subject’s ability to understand the normal progression of strengthening and mobility.
For this subject, the pain resolved dramatically immediately after surgery though a small amount persisted through the first year. The function and endurance begin to improve most markedly after range was restored by the six months post-operatively time frame but was noticeable month to month at 4, 5, and 6 months. Function continued to improve through the first year and beyond. Pain diminished as the endurance and strength improved over the course of the year. ASES function improved to 42/50 and 47/50 levels at one-year post-operative for the left and right arm, respectively.

**DISCUSSION**

Efficient upper extremity motion requires a stable base for functional arm and hand mobility; thus, proximal stability for distal mobility. The scapulothoracic is more proximal and considered the base for the glenohumeral joint and extremity. However, the scapulothoracic joint is predominantly a soft tissue joint. Injuries, such as a muscle rupture, affect the stability and can result in alterations in arm function. As such, when one muscle is ruptured, the antagonists are unopposed which compromises the muscle balance across the joint and alters the kinematics and function for activities such as pushing, pulling, lifting, and reaching.

These alterations in scapular thoracic stability and function, called scapular dyskinesis, have traditionally been considered to be due to neurological problems (long thoracic, accessory or dorsal scapular nerve palsies) or from muscle inhibition secondary to glenohumeral intra-articular disease which may require surgery. Non-surgical treatments for scapular dyskineses are usually exercises to help with motor control (ie, timing) or muscle strength at the scapulothoracic and trunk. Muscle tears, though common in the rotator cuff, are usually not part of the thought paradigm for scapulothoracic dyskinesis. This may explain, in part, why scapular muscle tears are not identified for several years after injury.

For this subject, success in rehabilitation was attributed to five specific interventions added to the Lexington protocol. First, having the therapist take the scapula and manually push it into retraction and elevation toward a position provided pain relief and served as a "starting" point for all other treatments. Without good passive mobility of the scapula, attempts to actively move the scapula through full range were impossible to perform without compensations.

The second intervention, stretching the tight tissues, follows easily from the first. Mobility deficits can be due to tissue tightness, decreased tone, or imbalances of tone with antagonistic muscles. The tight pectoralis and latissimus dorsi muscles protract and anteriorly tilt the scapula which created tension on the repair and symptoms. Stretching these anterior and short muscles daily was necessary to relieve symptoms and critical before any strengthening could occur, including isometrics.

The third intervention in the early stages of rehabilitation that decreased pain and improved the ability for proper kinematics with early stretches was the manual massage techniques to the lateral aspect of the infraspinatus and posterior humeral muscles. A fascial sheath extends from the medial aspect of the rhomboid and is continuous from the anterior surface of the rhomboid to the serratus magnus. There is also a superficial fascia that extends from the superior aspect of the latissimus dorsi muscle across the infraspinatus across to the spine of the scapula limiting mobility of the scapular humeral motion. Stabilizing the scapular in neutral and gently massaging the fascia one layer at a time with small ranges of passive arm motion helped to separate motion at the two joints and prepare for normal kinematics. Without this intervention, the fascial restrictions protracted the scapula which placed tension on the repair. In this case, instrumented soft tissue mobility was not performed.

The scapula provides stability for upper extremity motion and functions mainly in the mid to shortened range. Retraining the scapular thoracic muscles in a retracted position not in a protracted position was the fourth key intervention. Using a surface biofeedback device was an effective tool to isolate scapular retraction with a submaximal contraction rather than co-contraction. Surface EMG biofeedback was also helpful to assess the timing of the contraction and identify when fatigue occurred.

Finally, pre-operative education treatments to prepare the subject and household for the first weeks post-operatively were invaluable. This subject did not have any pre-operative education or expectations prior to the first surgery. Consequently, basic activities such as dressing and sleeping positions were learned by trial and error with pain being the instructor following the first surgery. For the second surgery, knowing how to perform these tasks without increasing stress on the repair made the initial post-operative weeks easier, relatively pain free, and increased compliance with the post-operative limitations to limit tension on the repair site.

Since the goal in the first six weeks post-operatively was to allow the repaired muscles to heal without formal therapy or oversight, the subject was solely responsible for assuring that the activities performed were helpful and not
harmful to the repair. The pre-operative treatments may also be used to identify and address tight muscles around the shoulder girdle in as a means of getting a "head start" on the post-operative phase. Additionally, limitations along the kinetic chain that prevents activities such as sitting in an upright posture can be addressed. By adding comprehensive pre-operative treatments, the associated impairments were minimized to provide for improved compliance and decreased pain.

In rotator cuff repair, the patients who exhibit poor compliance with post-operative restrictions in the first six weeks showed a relative risk of re-tear and nonhealing 152 times higher than that of a compliant patient. The unique demands and function of the scapular muscles place the patient at great risk of non-compliance in the initial post-operative phase where there is no formal therapy and the patient is unsupervised. This risk can be mitigated by providing a few pre-operative education sessions and empowering the patient so they can share responsibility for rehabilitation decisions.

CONCLUSION

Protocols for rotator cuff rehabilitation are not applicable in dealing with scapular muscular reattachment due to the scapular muscles' role in arm elevation. This case report shares a unique perspective as the subject went through this surgery on each arm and is a physical therapist. This program is meant to supplement the Lexington Clinic protocol and provide treating therapist with specific interventions that were key to reduce symptoms in this subject with pre-operative program being a unique addition.

Formal therapy begins at approximately 6 weeks with passive shoulder elevation limited to 90° for approximately 3 months. Full passive motion was re-established by 6 months with active range of motion lagging behind by 20°. Post-operatively, surgical pain resolved in about 2 weeks but the previous 5 years of symptoms such as arm heaviness, headache, referred pain was gone immediately after surgery. Function and strength took about 1 year to return to near normal levels with occasional symptoms of burning due to fatigue that still can recur on occasions.

CONFLICTS OF INTEREST

No authors have a conflict of interest related to this manuscript.

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REFERENCES


SUPPLEMENTARY MATERIALS

Appendix A

Appendix B
The Implementation of Therapeutic Alliance in the Rehabilitation of an Elite Pediatric Athlete with Salter-Harris Fracture: A Case Report

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Keywords: boat racing, movement system, physical therapy, salter-harris fracture

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Background/Purpose

Although research on the value of therapeutic alliance is prominent in other areas of health care, physical therapy research is limited. The purpose is to describe the incorporation of therapeutic alliance concepts throughout the rehabilitation of an elite pediatric athlete with a complicated recovery following a fracture to the distal femoral epiphysis.

Case Description

A 14-year-old male was referred to physical therapy following an open reduction and internal fixation to address a type IV Salter-Harris fracture of the right distal femoral epiphysis. Post-operative care included immobilization in a brace for six weeks and he initiated physical therapy for four weeks (post-op weeks 6-10). At 10-weeks post-injury his range of motion and strength were severely limited compared to expected post-operative milestones. Due to these deficits an arthroscopic debridement of the subject’s right knee, hardware removal, and manipulation under anesthesia was performed. The subject then reported to the physical therapist on post-operative day three for evaluation and treatment without bracing or weight-bearing restrictions.

Outcomes

The episode of care spanned 17 weeks and included 25 physical therapy sessions. To facilitate therapeutic alliance with the subject, clear communication and easily measurable goals were established and connected to the subject’s relevant needs as an athlete. The plan of care was divided into three phases using “chunking” techniques to establish the rehabilitation priorities. The subject demonstrated improved range of motion, strength and was able to return to hydroplane racing and won a national championship in his age group.

Discussion

The unique aspect of this case was the incorporation of therapeutic alliance concepts and techniques into the rehabilitative management of a subject with a complicated fracture to the distal femoral epiphysis. The physical therapist built trust with the subject and facilitated a successful return to elite hydroplane boat racing.

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INTRODUCTION

Developing a therapeutic alliance with subjects and their social support systems is paramount, especially when rehabilitating from injuries with limited existing knowledge on normative values for recovery. Often utilized in clinical psychology, therapeutic alliance is the combination of an emotional bond between the subject and clinician and involves a mutual agreement pertaining to the plan of care. Therapeutic alliance exists in situations where there is subject-therapist agreement on goals and an affective bond exists between the subject and the therapist. Although many definitions exist, several characteristics, including flexibility in treatment design, honesty regarding progress, attending to subject experience and admission of insecurity or being unsure how to proceed, have been shown to enhance rapport and therapeutic alliance.

Eight dimensions have been identified across which therapeutic alliance is built in physical therapy. Aspects of therapeutic alliance are emphasized when the physical therapist engages in shared decision making with their subjects. When physical therapists are successful in implementing therapeutic alliance and shared decision making these factors can improve subject adherence, subject satisfaction, and subject quality of life in healthcare settings. Utilizing this approach can help physical therapists individualize subject care, account for biopsychosocial factors, and facilitate conflict resolution.

In physical therapy, behavioral change is a key aspect to long term success with musculoskeletal conditions and should be addressed throughout the plan of care. Establishing a relationship with the subject where the subject feels “seen, heard, and believed” could enhance care and improve subject outcomes. This is important for all subject cases that physical therapists evaluate and treat, but can be beneficial when a subject is being seen for a condition where scientific evidence to inform the treatment approach is not substantial. One example of a condition with limited research to guide clinical decision making related to rehabilitation is a complicated fracture to the distal femoral epiphysis. These fractures account for approximately 7% of lower extremity fractures and up to 6% of all physeal fractures. Fractures to the distal femoral epiphysis can be difficult to manage and may result in severe complications such as poor healing, growth arrest (27.4% to 62%), loss of range of motion (4% to 24%), and these complications can result in substantial loss of function. Of all the long bones in the body, fractures to the distal femoral epiphysis are important to manage, because it is responsible for 35% of the total leg length attained through adolescence. Limited literature exists to assist and guide postoperative physical therapy decisions and management of femoral growth plate fractures. When the scientific evidence demonstrates the severity of the condition, but offers little guidance in post-operative rehabilitation, building rapport and therapeutic alliance is crucial for shared decision making.

The purpose of this case report was to describe the incorporation of therapeutic alliance concepts and techniques throughout the rehabilitation of an elite pediatric athlete with a complicated recovery following a fracture to the distal femoral epiphysis. Each of the eight described therapeutic alliance behaviors are defined with examples from this clinical case that demonstrate each characteristic. The importance of subject involvement in decision making and the development of therapeutic alliance across the episode of care were central to successfully rehabilitating the athlete with a return to full sport participation. Particular emphasis in this case study was placed on decision making related to appropriate rehabilitation progression, methods for maintaining subject engagement across an extended timeline, and specialized interventions to assist in return to competitive sports. The subject of this case report gave assent and parents provided permission for their case to be shared.

DESCRIPTION OF CASE

A 14-year-old, Caucasian male was referred to physical therapy after a complicated recovery following an open reduction and internal fixation of the distal femoral epiphysis. Prior to his injury, he was an active lacrosse player and nationally prominent hydroplane boat racer. Additionally, he was recreationally active in a variety of other sports, such as handball and lacrosse. He had no previous significant injuries and his medical history was unremarkable.

The subject initially sustained a type IV Salter-Harris fracture of the right distal femoral epiphysis while playing handball. A type IV Salter-Harris fracture is suggestive of a fracture compromising the epiphyseal plate, metaphysis, and epiphysis. The mechanism of injury occurred when he was running laterally, and in order to dodge a ball, he...
Table 1: Therapeutic Alliance and Shared Decision Making in Physical Therapy

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Therapeutic Alliance</th>
<th>Stages</th>
<th>Shared Decision Making</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Congruence in goals: Characterized by having similar expectations between therapist and subject.</td>
<td>1</td>
<td>Prepare for Collaboration: The physical therapist should facilitate subject involvement to determine decisions for plan of care and priorities of both the subject and physical therapist.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Connectedness and friendliness of the physical therapist: Characterized by kindness and engaging the subject.</td>
<td></td>
<td>Exchange Information: The physical therapist should determine the subject values and discuss the benefits and risks of different treatment options.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Communication style: including non-verbal body language and clarifying of information presented.</td>
<td></td>
<td>Affirm and Implement Decision: The plan of care is agreed upon by physical therapist and subject, and the priorities of both are reaffirmed.</td>
<td></td>
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<tr>
<td>4</td>
<td>Clear Expectations for the process: Clarity in goal setting for overall care and within sessions.</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Influencing factors: Addressing environment, physical therapist reputation, and subject life experiences.</td>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>Individualized Treatment: Care specific and responsive to the subject.</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>Partnership in decision making: Having the subject participate in decisions with physical therapist.</td>
<td>3</td>
<td></td>
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<tr>
<td>8</td>
<td>Establishing roles and responsibilities: Determine roles of subject and physical therapist including accountability for those responsibilities.</td>
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Table 2: Demands of Hydroplane Racing

<table>
<thead>
<tr>
<th>Description of Sport</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroplane racing involves riding small, motored boats across a lake along courses and in straight lines for speed.</td>
<td>Hydroplane racing involves riding small, motored boats across a lake along courses and in straight lines for speed. Participants kneel in a crouched position behind the steering wheel and utilize their lower extremities to absorb shock and guide the boat across wake in the water. Various classes exist, including technical classes that emphasize change of direction and controlled maneuvering, as well as straight line racing. Racers attain speeds of up to 50 MPH while racing.</td>
</tr>
<tr>
<td>Active shoulder flexion range of motion of 160° is preferred.</td>
<td>Active shoulder flexion range of motion of 160° is preferred. Sustained pressure needs to be maintained on steering wheel therefore adequate shoulder and upper arm strength is required.</td>
</tr>
<tr>
<td>Adequate trunk stabilizer strength is a key component to maintaining balance while utilizing arms to stabilize the boat and legs to control for unpredictable changes from the boat.</td>
<td>Adequate trunk stabilizer strength is a key component to maintaining balance while utilizing arms to stabilize the boat and legs to control for unpredictable changes from the boat.</td>
</tr>
<tr>
<td>Need to be able to maintain crouch position with hips approximately in line with knees in the sagittal plane. (Hip flexion &gt; 125° knee flexion &gt; 130° pending limb girth)</td>
<td>Need to be able to maintain crouch position with hips approximately in line with knees in the sagittal plane. (Hip flexion &gt; 125° knee flexion &gt; 130° pending limb girth) Minimum of 5/5 hip strength in all directions with manual muscle testing.</td>
</tr>
<tr>
<td>In order to assume proper crouch position in boat, a minimum of 130° of knee flexion is required.</td>
<td>In order to assume proper crouch position in boat, a minimum of 130° of knee flexion is required. Quadriceps strength is extremely important to maintain proper position.</td>
</tr>
<tr>
<td>Full closed chain dorsiflexion is required to maximize success.</td>
<td>Full closed chain dorsiflexion is required to maximize success.</td>
</tr>
<tr>
<td>Racers are commonly barefoot or wear minimalist shoe apparel and need to be able to balance on a boat changing direction and adjust various wakes in the water.</td>
<td>Racers are commonly barefoot or wear minimalist shoe apparel and need to be able to balance on a boat changing direction and adjust various wakes in the water.</td>
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range of motion, poor gait mechanics, and limited strength, prompting a second opinion from another orthopedic surgeon. Based on follow-up imaging and clinical consultation, the decision was made to proceed with an arthroscopic debridement of the subject’s right knee, hardware removal, and manipulation under anesthesia. Surgery was successful at normalizing range of motion of the knee. While under anesthesia, the surgeon noted 0° degrees of extension and 120° flexion range of motion. The subject then reported to physical therapy on post-operative day three for evaluation and treatment without bracing.

EXAMINATION AND EVALUATION (TABLE 3)

The subject reported to physical therapy using a single axillary crutch in the opposite upper extremity for ambulation with post-operative instructions of weight-bearing as tolerated. He demonstrated decreased range of motion, swelling and poor quadriceps activation as measured by quadriceps lag on straight leg raise that would be considered normal for his overall episode of care and post-operative state (15° extension lag with straight leg raises).15–18 The subject ambulated with a limp, and visual assessment by physical therapist suggested decreased stance time on the right foot and lack of terminal knee extension due to knee stiffness, and was limited to approximately a 20° knee extension deficit at mid-stance and inability to fully weight shift onto the right lower extremity.16,19–21 No signs of infection or neurovascular compromise were present, and all incisions were clean, dry, and appropriately dressed with sutures intact.22–25 Marked reduction in soft tissue mobility of the quadriceps and hamstring was noted with palpation as perceived by physical therapist and subject, as well as patellar hypomobility with less than one quadrant of mobility in all planes of movement. Bruising was minimal at time of evaluation, and effusion of the knee joint was measured at a 2+ using the sweep test.26

SUBJECT’S GOALS

After discussion with the subject and his parents, the subject’s primary goal of physical therapy was full return to competitive hydroplane racing at the elite level (Table 2). The subject was a competitive lacrosse player, and an elite hydroplane athlete (placed third nationally in his age group the previous year). The subject and his father briefly discussed hydroplane racing, and the physical therapist observed several videos of the subject in previous competitions. The demands of the sport were appraised by the treating physical therapist (Table 2).

THREATS AND OPPORTUNITIES FOR THERAPEUTIC ALLIANCE

This case presented several challenges to developing therapeutic alliance with the subject and parents. The subject’s previous experience with physical therapy was suboptimal and he yielded a poor outcome from the surgery, which created an environment where distrust in the rehabilitation process was understandable. His parents and the subject had concerns about him undergoing two substantial knee surgeries at such a young age. This also detracted from therapeutic alliance, and could impact care by decreasing compliance with treatment recommendations.Treating a subject in adolescents presents unique challenges compared to treating adults, because there are several interactions to consider with the therapeutic alliance and shared decision making: the subject with the physical therapist, the subject and parents, and the physical therapist and parents. However, in such a case where many factors would challenge the subject-parent-physical therapist interaction, strategies can be used to emphasize and build therapeutic alliance.4,6–8,11 This was accomplished in the evaluation through clear communication and emphasized in the creation of the plan of care for his episode. Goals were based on objective measures (Table 3), demands of hydroplane boat racing (Table 2), and phases of post-operative rehabilitation (Table 4). The subject’s progress in each phase was assessed in several ways. Gait was appraised visually by the physical therapist, return to functional exercise and sport related tasks was self-report, and objective measures of strength, range of motion and swelling assessment were taken with goniometer, sweep test, manual muscle testing, isokinetic and isometric strength testing with electromechanical dynamometer (Biodex System III Dynamometer, Biodex Medical Systems, Shirley, NY), and one repetition maximum testing on gym equipment such as leg press and knee extension machines.27–33

DEVELOPMENT OF THE PLAN OF CARE

PLAN OF CARE DEVELOPMENT

To facilitate a therapeutic alliance with the subject, the physical therapist determined that clear communication and objective, easily measurable goals would be most beneficial to maintain the focus of the subject and his family in their efforts. The subject and his father expressed anxiety about the many complications and limitations, and both were unsure how to begin the rehabilitation process. The subject seemed unsure of rehabilitation and the pain he felt with movement, and was reported to be at risk of non-compliance by his father, particularly if he could not return to sports that he found meaningful (e.g. hydroplane racing and lacrosse). In order to help manage these concerns, a subject-centered phased rehabilitation plan of care with goals/milestones was designed with the subject for advancing rehabilitation and returning to sports at the end of the first visit. Each subsequent stage was connected to the subject’s relevant needs as an athlete.

The plan of care was divided into three phases using “chunking” techniques to establish the rehabilitation priorities.34–36 Chunking, or grouping information into smaller, easy to remember pieces, was utilized in order to enhance recall of the stages in order to minimize risks of non-compliance.34–36 For each stage, the subject and physical therapist each developed 2 to 3 goals that would signal he was ready to progress his activity, and selected which goals would be most relevant to use (Table 4). The value of subject input in the development of goals is well documented, and a significant portion of the evaluation was spent developing these goals.1–4,6 By improving recall and establishing clear
Table 3: Objective Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>Initial Measure</th>
<th>Final Measure (Week 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROM* (°)</td>
<td>3-75</td>
<td>0-135</td>
</tr>
<tr>
<td>AROM* (°)</td>
<td>8-60</td>
<td>0-135</td>
</tr>
<tr>
<td>Quadriceps tone</td>
<td>Poor, limited activation</td>
<td>No deficit noted</td>
</tr>
<tr>
<td>MMT Quadriceps</td>
<td>Deferred due to acuity of surgery</td>
<td>5/5</td>
</tr>
<tr>
<td>MMT Hamstrings</td>
<td>Deferred due to acuity of surgery</td>
<td>5/5</td>
</tr>
<tr>
<td>HS length (90/90)</td>
<td>-50°</td>
<td>-10°</td>
</tr>
<tr>
<td>Modified Stroke</td>
<td>3+</td>
<td>0</td>
</tr>
<tr>
<td>Patellar Mobility</td>
<td>Hypomobile, Pain free</td>
<td>Normal mobility, Pain free</td>
</tr>
<tr>
<td>Tibiofemoral Mobility</td>
<td>Hypomobile, Painful</td>
<td>Normal mobility, Pain free</td>
</tr>
<tr>
<td>Quadriceps Symmetry (60 degrees/second)</td>
<td>Not Tested</td>
<td>80%</td>
</tr>
<tr>
<td>Quadriceps Symmetry (300 degrees/second)</td>
<td>Not Tested</td>
<td>91%</td>
</tr>
<tr>
<td>Hamstring Symmetry (60 degrees/second)</td>
<td>Not Tested</td>
<td>89%</td>
</tr>
<tr>
<td>Hamstring Symmetry (300 degrees/second)</td>
<td>Not Tested</td>
<td>121%</td>
</tr>
</tbody>
</table>

PROM: passive range of motion; AROM: active range of motion; MMT: manual muscle testing; HS: hamstring.

*Range of motion shorthand interpretation. The first number refers to the knee extension value, and the second number refers to the knee flexion value. For a ROM assessment of 3-75, this can be interpreted as the subject lacking 3° of knee extension and only yielding 75° of knee flexion. A reading of 3-0-120 would indicate that the subject has hyperextension of the knee by 3° and 120° of flexion.

Table 4: Stages of Rehabilitation and Goals

<table>
<thead>
<tr>
<th>Stage</th>
<th>Goals</th>
<th>Therapeutic Alliance Competencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1: Restore ROM (weeks 0-4)</td>
<td>1. Knee ROM 5°-85° or greater</td>
<td>1. Congruence in goals</td>
</tr>
<tr>
<td></td>
<td>2. 0 Edema (modified sweep)</td>
<td>2. Communication Style</td>
</tr>
<tr>
<td></td>
<td>3. Gait with ≤ 5° extension lag</td>
<td>3. Partnership in Decision Making</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Influencing Factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Establishing Roles and Re-sponsibilities</td>
</tr>
<tr>
<td>Phase 2: Strengthening (weeks 5-10)</td>
<td>1. Knee ROM: 0°-125° or greater</td>
<td>1. Connectedness</td>
</tr>
<tr>
<td></td>
<td>2. Gait: No visual limp</td>
<td>2. Clear Expectations for the process</td>
</tr>
<tr>
<td></td>
<td>3. SL leg press ≥ 50% of 1RM on unaffected limb by week 6; ≥ 80% by week 8</td>
<td>3. Individualized Treatments to the subject</td>
</tr>
<tr>
<td></td>
<td>4. SL knee extension ≥ 50% of 1RM on unaffected limb by week 6; ≥ 80% by week 8</td>
<td></td>
</tr>
<tr>
<td>Phase 3: Return to Sport (week 11 and beyond)</td>
<td>1. Full tuck position for racing</td>
<td>1. Partnership in Decision Making</td>
</tr>
<tr>
<td></td>
<td>2. Jog x 5 minutes without pain</td>
<td>2. Accountability for responsibilites</td>
</tr>
<tr>
<td></td>
<td>3. Isokinetic Quad symmetry ≥ 80% unaffected limb on electromechanical dynamometer</td>
<td>3. Clear Expectations for the situation</td>
</tr>
<tr>
<td></td>
<td>4. Return to racing competitively</td>
<td></td>
</tr>
</tbody>
</table>

ROM: range of motion; SL: single leg; RM: repetition maximum.

Priorities with the collaboration of the subject and his parents, therapeutic alliance was enhanced. In order to assess progress, the goals for each stage were measured at the start and finish of each session, and the subject was asked to reflect on his progress after each visit.

**PHYSICAL THERAPY AND THERAPEUTIC ALLIANCE INTERVENTIONS THROUGH THE STAGES**

The criteria for progression through the phases of rehabili-
tation focused on protection of the surgery and restoration of range of motion within the first four weeks (Figure 2). Once full knee extension (0°) was achieved, knee flexion as within normal limits (approximately 125°), and the surgeon was satisfied with bone healing from the surgery, the focus of the rehabilitation plan turned to strengthening. When Phase 2 goals were met, the focus shifted to sports specific exercises and achieving the necessary strength to prevent future injury and enhance performance. A primary measure of this was isokinetic quadriceps symmetry > 80% of the unaffected limb on electromechanical dynamometer (Biodex System III Dynamometer, Biodex Medical Systems, Shirley, NY) testing and performance of sports specific tasks.

PHYSICAL THERAPY PHASE 1: RESTORATION OF RANGE OF MOTION (TABLES 3 & 4)

Phase 1 interventions targeted restoring total knee range of motion to within 75% of his uninvolved knee, as well as reducing swelling and increasing knee extension during midstance and push off phases of gait cycle. During this stage of rehabilitation, which lasted about four weeks, all eight aspects of building therapeutic alliance (Table 1) were demonstrated. Significant time was spent each session educating the subject and his parents about the severity of the injury, as well as establishing goals for each stage with subject and family feedback were important factors related to his success. During the initial evaluation, the subject’s parents expressed concerns about the large number of impairments, including weakness, limited range of motion, swelling, and abnormal gait pattern, and felt overwhelmed by the number of problems he had developed. Acknowledgment of the number of issues, as well as open communication regarding goals of each stage of rehabilitation significantly improved therapeutic alliance with the subject and resulted in a high degree of “buy-in” from the subject and his parents. The number of deficits present and the complications that occurred to date in the case made the end goal of returning to sport seem distant and unattainable. Through goal setting during each phase of the rehabilitation, the calm demeanor of the physical therapist, and shared decision making to make an individualized plan, the subject and his parents felt comfortable that this physical therapist could help the subject obtain his goal of return to sport.

Congruence in goals and expectations were created by having the subject and his father define hydroplane racing as their primary goal, and acknowledging and accepting this as the primary goal for the episode. Limited research guides the prognosis for such a case, the treating physical therapist was open about this, and this honesty in communication helped to establish a connection with both the subject and his family, enhancing the therapeutic alliance. Interventions that build trust, including manual therapy techniques that have been shown to improve range of motion, pain, and function, as well as build rapport with the subject were included. Manual therapy was used as a staple of therapy at this stage to decrease pain and improve range of motion, which further established therapeutic alliance. 14,37–42 During therapeutic exercise and manual therapy sessions, the subject provided input on the intensity of the intervention and if it was meeting the goal of increasing range of motion, and treatments were adjusted based on his input. By allowing the subject partnership in the rehabilitation process to help structure the session, it developed communication and clear expectations for the treatment, as he gained trust with the physical therapist the therapeutic alliance appeared to be improved. An example of this occurred when the subject reported that he was fatigued with manually stretching his knee in clinic, and wanted to ride a stationary bicycle to increase range of motion. After educating him about the needed requirements to increase his mobility with seat settings, the subject elected to use the stationary bicycle on a setting that would require additional motion beyond which was measured at the start of the session. He would rock his knee back and forth, self-mobilizing, until he was able to complete a revolution on the bike.

The rapport and trust between the subject and the physical therapist enhanced home exercise adherence during Phase 1 intervention. Although adherence to the home exercise program was self-reported by the subject, the physical therapist created a relationship with the subject that emphasized honesty. Because of the strong rapport and therapeutic alliance developed, the physical therapist felt the self-report of home exercise program adherence was accurate. In addition to his home exercise program, the subject created his own passive range of motion mechanism using a recliner at home. He demonstrated significant commitment to the goal of regaining his range of motion, above and beyond just performing his prescribed home exercise program. This commitment helped to maintain an orderly progression in the early stages of rehabilitation, and established a foundation of trust for future stages.

PHASE 2: STRENGTHENING THERAPEUTIC ALLIANCE & INCREASING FUNCTIONAL MOBILITY (TABLE 4)

Phase 2 interventions targeted increasing strength of the quadriceps, hamstrings, and translating these strength gains into functional mobility needed for sports participation. Interventions from the previous stage were phased out, and replaced with resisted active range of motion and weight bearing exercises. At the start of this phase of rehabilitation, most bilateral activities resulted in a large weight shift, assessed visually, onto the uninvolved limb. 43 In order to address excessive weight-shifting onto the uninvolved limb, exercises were performed in front of a mirror for visual
feedback, and verbal and tactile cues were given to enhance feedback and improve loading/shifting weight on the right knee. The physical therapist engaged the subject by providing verbal cues requiring the subject to interact, including asking the subject if he felt his loading was equal on the left and right limb and self-grading of his movements after completion. While performing the exercises, the subject was asked how he thought the repetition went, and what he would recommend to change the movement. When he was unsure how to address what he saw, the physical therapist provided cueing to assist in changing the exercise, but emphasis was placed on the subject providing feedback to the physical therapist. This helped to establish the subject as a valued contributor to the sessions, and further strengthened the therapeutic alliance. Key aspects of the therapeutic alliance that were built and reinforced during this stage included clear communication, building of connection between the physical therapist and the subject, individualized treatments based on subject needs, and shared decision making on when to adjust interventions.

At the end of this stage, the subject expressed frustration that his strength was not progressing fast enough. Strength gains in Phase 2 prior to isokinetic testing are highlighted in Figure 3. He verbalized that he had low motivation to perform home exercises, and self-progressed to jogging. The return to jogging criteria had not been met and the subject had not been cleared by the physical therapist to jog. A limb symmetry index of 80% is recommended before attempting to jog. To manage this frustration, the subject and physical therapist agreed that he would begin performing sport-like motions for hydroplane racing, and would be allowed to jog in the clinic as long as he did not advance his activity level on his own at school. This was a compromise made by the physical therapist to gain control of what the subject was doing for his home exercise program. Through shared decision making the subject and physical therapist compromised on only running in clinic in a controlled environment and not outside on his own. Risks of progressing too early into sports, including re-fracture of the femur, iatrogenic injury to other joints due to poor strength, and potential long-term changes to movement patterns due to maladaptive loading were explained to the subject and his parents. The parents and subject understood these concerns, and the parents provided consent to progress into higher level activities. Although adequate healing should have occurred by this point, a methodical conservative progression was advised for an optimal outcome and prevent any relapses or exacerbation of pain. Without establishing a strong therapeutic alliance, it is likely that the subject may have had a suboptimal outcome due to self-progression. However, the subject admitting and expressing this frustration was facilitated directly from the trust he had built with the physical therapist.

PHASE 3: THERAPEUTIC ALLIANCE AND RETURN TO SPORT (TABLE 4)

During the final stage of rehabilitation, the subject began sport specific training aimed at returning to hydroplane racing. This stage provided an excellent opportunity for therapeutic alliance by creating partnership in decision making, building and establishing new roles and responsibilities, and using the rehabilitation environment to enhance the rehabilitation process. The subject reported that he would prefer to work on hydroplane racing as much as possible during this stage, as his national competition was approaching. In order to better understand the demands of hydroplane racing, pictures of equipment were brought into the clinic and video analysis of the subject’s previous races were led by the subject and his father. This instruction helped the subject and his father feel heard, and helped the physical therapist understand the demands of the sport (Table 2). They focused on specific maneuvers to steer the boat, as well as emergency evasive maneuvers and procedures when crashes occurred and the racer was ejected from the boat. In these meetings, the subject led the meeting providing insight into the sport, and this cemented the rapport developed with the subject across the plan of care, and minimized any fear-avoidance beliefs from both the subject and his family. By better understanding the sport, the physical therapist was able to target interventions that helped the subject and his parents develop confidence in his ability to safely return to sport. The subject was able to feel comfortable knowing that the physical therapist understood his sport, as he had taught the physical therapist how racing worked. The subject and his father changed their roles, and became leaders of the rehabilitation team by providing instruction on racing. They were able to help create safe return to activity criteria, and then provided video analysis of the subject performing practice runs to more specifically target interventions as the stage came to a close. This relationship helped set the stage for a safe return to competition, and the authors feel that the therapeutic alliance was central to his return to competition.

This stage also utilized the rehabilitation environment to help build confidence. In order to safely evaluate if the subject could handle steering the boat, rehabilitation equipment was modified and used to create a dynamic surface that the subject could “ride” and “steer” by manipulating his body weight. Early interventions challenged the subject to return to the crouched position required to sit in the cockpit of his boat on the ground. A graded-exposure approach to intervention selection was taken to challenge balance, strength, reduce fear, and boost confidence. The interventions started with a static tuck on a solid surface,
and as he gained confidence, the subject was challenged to perform weight shifting and upper extremity motions such as rowing and shoulder extension while in a tuck. This replicated an unstable surface similar to what he dealt with while racing over water, and he progressed from static holds to weight shifting and reaching while on the BOSU (Figure 4). By modifying equipment in the environment, the therapeutic alliance was once again enhanced, and helped to build confidence that when he completed the rehabilitation process he would be safe to boat again.

**DESCRIPTION OF OUTCOMES**

The episode of care spanned 17 weeks and included 25 physical therapy sessions. Objective data and subject reported outcomes are listed in Table 3. The subject demonstrated substantially improved knee range of motion, and was able to comfortably sit in the crouched position required for hydroplane racing. Strength of the quadriceps and hamstrings also improved, with the lowest symmetry identified in force production of the quadriceps at 60°/sec during isokinetic testing (Table 3). These speeds were extrapolated from ACL reconstruction guidelines and return to sport criteria. He was cleared by the surgical team to return to full activity, and encouraged to continue with his home exercise program. The subject was able to return to hydroplane racing without impairments and minimal compensations in gear and boat set up, and won a national championship in his age group. Subject reported outcomes were not collected at the end of episode of care, as the subject missed his discharge appointment due to illness.

**SUBJECT PERSPECTIVE AND POST-PHYSICAL THERAPY FOLLOW UP**

The physical therapist contacted the subject through electronic mail (e-mail) five years from his last visit after the surgery to get an update and to have him fill out various subject reported outcome measures regarding general health, knee function, fear of movement and therapeutic alliance. The subject responded with the following message:

“Lacrosse and racing the past couple years has been so much fun and I couldn’t thank you enough because you were a part of my journey to getting back on track. I play lacrosse now at [removed for subject privacy] University and I actually played in all six games this year. I also led all freshmen in ground balls and third overall on the team for groundballs... Being a part of that lacrosse team has been a blessing, the people I have met are so kind, but have also pushed me to become a better person and student. Racing has been another blessing in my life. I have met so many people and learned so many great life lessons from it! You helped me return to that racing season in the summer of 2015 to win my first national championship. Now the crazy part here is after that I have gone on to win six more national championships and have received three hall of champions inductions. Honestly, boat racing would not have been the same without my treatment from OSU and you.”

Although the emphasis of this case is on therapeutic alliance there was no formal evaluation of this during the subject’s time with the physical therapist, so the subject and physical therapist completed a survey regarding therapeutic alliance retroactively. The Working Alliance Inventory (WAI) measures three domains of therapeutic alliance: 1) agreement between therapist and subject regarding goals of a given treatment, 2) agreement between therapist and subject regarding tasks to achieve set goals, 3) Quality of bond between therapist and subject. The subject scored a total WAI score of 70 (Goal items: 21, Task items: 21, Bond items: 28). The physical therapist scored a total WAI score of 69 (Goal items: 22, Task items: 21, Bond items: 26). The similarity in scores between the subject and physical therapist suggest high therapeutic alliance between them.

The subject also completed the Lower Extremity Functional Scale (LEFS), the Fear Avoidance Belief Questionnaire (FABQ), and the Tampa Scale of Kinesiophobia (TSK). He scored an 80 out of 80 on the LEFS suggesting full lower extremity function. He demonstrated low fear with scores on FABQ physical activity scale on of 5 and work subscale of 0, and low fear of movement on the TSK with a score of 29.

**DISCUSSION**

Within care for musculoskeletal conditions, therapeutic alliance has been identified as an area of emphasis for research and understanding due to the potential link between therapeutic alliance and adherence. Outside of musculoskeletal conditions, therapeutic alliance has been used to enhance commitment to behavioral change. These changes have been studied in medicine and psychology, and demonstrate that therapeutic alliance enhances outcomes in chronic disease care, and enhances adherence to treatment recommendations. It has been linked to improved quality of life, subject satisfaction, and psychological well-being. When working with medical specialists, subjects felt that the specialist being present in the moment, allowing them to feel like they were “seen, heard, and believed” was a...
In this case, therapeutic alliance techniques were used to facilitate education and communication with the subject, improve exercise/activity compliance, enhance exercise interventions, and augment other techniques focused on restoring and return to high levels of activity. This may shorten the overall episode of care and improve clinical decision making for progression of activity and identification of needs for early referral back to other medical disciplines. Therapeutic alliance has been shown to improve motivation and outcomes in chronic low back pain, as well as improving adherence to home exercise programs.\(^\text{9-11}\) In this case, the subject provided feedback on interventions in the early stages, contributing directly to evaluating the interventions addressing his limitations. In the later stages of rehabilitation, the subject provided the therapist with substantial input and feedback to create relevant interventions that would have been missed without an intimate understanding of his sport. Even when he attempted to self-progress back to sports before meeting the therapeutic goals, the established therapeutic alliance allowed for an open conversation and the therapist and the subject were able to reach a compromise that maintained his safety and helped him continue to progress. Without a strong therapeutic alliance, these conversations may result in non-compliance with recommendations and possible subject injury due to inappropriate progression.\(^\text{10}\)

**LIMITATIONS AND FUTURE RESEARCH**

This case report has several limitations. Case reports represent a low form of evidence to inform clinical decision making, and further research is needed to validate the concepts discussed in this case. Also, cause and effect cannot be determined in this case report, and it is possible he could have improved with time from the surgery and without intervention. Although research on the value of therapeutic alliance is prominent in other areas of health care, physical therapy research is limited. Further, limited data exists for appropriate timing of progression of interventions following repair of epiphyseal fractures. Although inventories exist to measure therapeutic alliance, none were utilized as part of the standard care provided at the treating facility and was not objectively quantified until five years after the last visit. Future case reports and research studies should consider valid and reliable forms of therapeutic alliance measurement such as the WAI throughout the plan of care.\(^\text{47,50}\)

Although the case demonstrates the physical therapist and subject accomplished all three of the aforementioned domains, the case report would have been strengthened with an objective measurement of therapeutic alliance throughout the plan of care, rather than retroactively obtaining these measures.\(^\text{47,50}\)

The authors suggest that measuring therapeutic alliance would be a useful adjunct to clinical care in complicated and chronic cases, and cases where progression is limited, as it may provide insights into factors that may contribute to slow progression. This case provides guidance for the sequencing of interventions specific to injuries of the distal femoral epiphysis, but to the authors’ knowledge, there is not a specific sequence of events to build therapeutic alliance, and so the authors encourage clinicians to use this as a guideline rather than an absolute series of steps.

**CONCLUSION**

Therapeutic alliance may be used to improve subject outcomes and enhance care provided for musculoskeletal conditions. The authors feel that using therapeutic alliance concepts enhanced communication and rapport with the subject and limited his frustration and preemptive attempts to self-progress too quickly for his physical state. Factors related to success in this case included initial “buy-in” of the subject and his family to the rehabilitation plan through their direct input in creating measurable goals to progress through the stages of his rehabilitation. Clinicians should be mindful of therapeutic alliance during the initial evaluation, and therapeutic alliance should continue to be built across the episode of care. It is recommended that clinicians utilize similar techniques to assist in the management of complicated cases and help guide decision making when limited literature exists on injuries such as the one described in this case.
CONFLICTS OF INTEREST

Authors have no financial disclosures or conflicts of interest related to this project.

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REFERENCES


Clinical Commentary/Current Concept Review

Visual Perturbation to Enhance Return to Sport Rehabilitation after Anterior Cruciate Ligament Injury: A Clinical Commentary

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Keywords: stroboscopic glasses, rehabilitation, acl, anterior cruciate ligament

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Anterior cruciate ligament (ACL) tears are common traumatic knee injuries causing joint instability, quadriceps muscle weakness and impaired motor coordination. The neuromuscular consequences of injury are not limited to the joint and surrounding musculature, but may modulate central nervous system reorganization. Neuroimaging data suggest patients with ACL injuries may require greater levels of visual-motor and neurocognitive processing activity to sustain lower limb control relative to healthy matched counterparts. Therapy currently fails to adequately address these nuanced consequences of ACL injury, which likely contributes to impaired neuromuscular control when visually or cognitively challenged and high rates of re-injury. This gap in rehabilitation may be filled by visual perturbation training, which may reweight sensory neural processing toward proprioception and reduce the dependency on vision to perform lower extremity motor tasks and/or increase visuomotor processing efficiency. This clinical commentary details a novel approach to supplement the current standard of care for ACL injury by incorporating stroboscopic glasses with key motor learning principles customized to target visual and cognitive dependence for motor control after ACL injury.

Level of Evidence
5

INTRODUCTION

Anterior cruciate ligament (ACL) tears are common orthopedic injuries,¹ involving an extensive plan of care and physical therapy following surgical reconstruction.² Despite receiving comprehensive approaches to restore knee function, quadriceps strength,³⁴ and joint stability,⁵⁻⁷ re-injury rates remain high, especially among young female athletes.⁴,⁸⁻¹⁷ This increased risk of re-injury may stem from nuanced neuromuscular consequences of ACL injury that therapy may not adequately address.

While ACL tears are peripheral joint injuries, the combination of effusion, pain, mechanical instability and deafferentation secondary to loss of joint mechanoreceptors may modulate central nervous system (CNS) reorganization.¹⁸,¹⁹ The CNS reorganization manifests as proprioceptive deficits and impaired motor coordination secondary to increased attentional, cognitive²⁰⁻²³ and visual relative to proprioceptive processing demands for motor control,²⁰⁻³⁵ A potential avenue to augment ACL rehabilitation is to facilitate sensory reweighting (nervous system adjustment of relative sensory input/processing for motor control) by shifting the post-injury reliance on vision for motor control to remaining proprioceptive inputs (e.g., the joint capsule, other ligaments, muscle spindles). Specifically, the use of visual perturbation training, which aims to reduce visual input availability during standard rehabilitative exercises, may reduce the dependency on vision and reweight neural processing toward proprioception and/or increase visuomotor processing efficiency.³⁶ Additionally, the application of key motor learning principles may support visual perturbation training, such as 1) an external visual focus of attention or cueing to help ensure visuospatial demands during training and 2) implicit learning to reduce the cognitive requirements for motor control and promote movement automaticity.³⁷⁻⁴⁰ The following commentary details an example of a sensory reweighting protocol that combines the use of stroboscopic glasses and key motor learning principles.

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BEHAVIORAL SUPPORT FOR INCREASED VISUAL RELIANCE & NEUROCOGNITIVE MOTOR PLANNING FOLLOWING ACL INJURY

INCREASED VISUAL RELIANCE

A series of investigations in ACL deficient (ACL-D) and reconstructed (ACL-R) patients provide support for increased visual reliance for motor control. During postural control tasks, patients with ACL injuries and uninjured controls performed similarly when vision was unobstructed. However, when vision was perturbed, patients with ACL injuries performed significantly worse (e.g., increased postural sway, failure in task completion). While a recent meta-analysis indicated patients with ACL-R are not as dependent on vision for postural control as patients with ACL-D, the mixed finding may be secondary to not challenging knee control during single-leg stance (by allowing a straight leg position), static postural control not being sufficiently challenging in those with reconstruction or complete vision obstruction not perturbing visuospatial processing sufficiently to elicit a deficit. This is exemplified by patients with ACL-R being more affected by visual perturbation (i.e., stroboscopic glasses) during drop landing and the transition from double to single leg stance with eyes closed and when challenged with visuocognitive tasks relative to matched controls.

An increased weighting towards visual input and processing for postural and lower extremity motor control following ACL injury may emerge from a sensory reweighting phenomenon that is driven, in part, by the underlying joint tissue and ligament mechanoreceptors. These mechanoreceptors, including Ruffini and Pacinian corpuscles, provide information about joint position, motion and acceleration, and their loss compromises proprioception and functional stability. Consequently, the CNS may employ functional strategies, such as sensory reweighting to more reliable stimuli (e.g., vision, vestibular), or increase cognitive and attentional processes to maintain adequate motor control. The Bayesian optimal integration model details how weighting sensory stimuli by reliability reduces the uncertainty of perception, thereby optimizing performance. Further, physical therapy following ACL injury may also increase visual attention to the knee, as clinicians primarily utilize visually-dominated exercises and provide feedback with an internal focus of attention (i.e., emphasizing movement kinematics or muscle activation, rather than movement actions) to the injured joint. However, weighting vision to guide lower limb movement may be maladaptive for athletes returning to a competitive sport environment, where the high demand to integrate dynamic visual information may limit the CNS's capacity to allocate neural resources to guide movement. Therefore, patients with ACL injuries may benefit from therapeutic interventions that encourage sensory reweighting from vision towards proprioception for motor control.

INCREASED NEUROCOGNITIVE MOTOR PLANNING

Excessive knee valgus has been identified as a major risk factor for primary and secondary ACL injury, with high sensitivity (78%) and specificity (73%). Herman and Barth identified a significant relationship between baseline neurocognition and knee valgus motion, where those with lower visual-memory and neurocognitive ability demonstrate increased knee valgus motion during a drop-landing task involving an unanticipated rebound immediately after landing. These studies suggest an athlete's baseline neurocognitive function may contribute to his or her risk of injury. A common therapeutic modality used to target neurocognitive function is dual-tasking, which involves the completion of two or more tasks simultaneously (e.g., balancing on one leg while counting down from 1,000 by 7). For example, patients with ACL injuries exhibit higher dual task-related costs during postural stability, gait and balance tasks. Taken together, following ACL injury, patients may experience a reduced capability to simultaneously engage in cognitive processing and motor performance. Neural mechanisms for this deficit may be secondary to the disruption of typical ACL afferent information utilized by the primary motor cortex, which may result in increased frontal activity (e.g., presupplementary motor area, supplementary motor area) to compensate. Thus, the cognitive demands of sport may exceed the patient's capability to optimally attend to external visual stimuli (e.g., opponents, balls) and maintain low injury-risk biomechanics.

NEUROIMAGING INVESTIGATIONS FOLLOWING ACL INJURY

ACL INJURY ASSOCIATED VISUOMOTOR & VISUOSPATIAL BRAIN ACTIVATION

Cross-sectional studies using functional magnetic resonance imaging (fMRI) have assessed neural activation differences for knee motor control in patients with ACL-D and ACL-R compared to uninjured, matched controls. In patients with ACL-D ~two years post-injury, fMRI identified increased activation in the posterior inferior temporal gyrus during a unilateral knee flexion/extension task. The posterior inferior temporal gyrus has been implicated in the recognition of biological movements, such as gait-like motion, rather than random motion. For patients with ACL-R ~3 years post-surgery, fMRI further identified increased neural activity within the lingual gyrus for both knee and combined hip-knee coordinated movements. The lingual gyrus is involved in the cross-modal integration of congruent visual and tactile stimuli in a spatially-specific manner. Increased neural activity requirements for the posterior inferior temporal gyrus and lingual gyrus corroborate the behavioral investigations, indicating an increased reliance or shift in visual information processing during motor control following ACL injury.

ACL INJURY ASSOCIATED NEUROCOGNITIVE MOTOR PLANNING BRAIN ACTIVATION

Other regions with increased neural activity include the presupplementary motor area in patients with ACL-D ~two years after injury as well as the frontal gyri, inferior frontal pole, paracingulate gyrus and anterior cingulate gyrus for...
patients with ACL-R ~five years post-surgery.22,69 While both injured populations performed identical tasks, differences in neural activation patterns are likely attributed to demographic (high vs. low functioning patients, activity level), surgical, time from injury, and rehabilitation protocol differences. Increased activation of the presupplementary motor area in patients with ACL-D may reflect increased cortical activity for planning simple movements.69 Increased activation across the frontal lobe in regions responsible for motor control further supports the hypothesis that patients with ACL injuries utilize increased cognitive resources for motor control by engaging in less efficient neural activation strategies.22 Neural efficiency refers to the reduced neural activity requirements of experts to perform a learned skill or task relative to novices, suggesting relative magnitude of neural activity scales with expertise and the ability to handle more complex coordination or environmental perturbations.75–78

The lack of neural efficiency and associated frontal region activity is corroborated with electroencephalography (EEG), indicating increased frontal theta power during force control and joint position tasks in patients with ACL-R ~one year post-surgery compared to uninjured controls.20,21 Frontal Theta power is an indicator of focused attention and task complexity,20 which may indicate that simple knee force control and joint position tasks are more complex and require greater attention for patients with ACL-R. Additionally, EEG has revealed that patients with ACL-D require more cognition/attention resources relative to healthy controls during walking, running and landing tasks as evidenced by significant increases in delta, theta, alpha, and beta band power, as well as asymmetry of the beta band power across the frontal and parietal lobes during jogging and landing.79 Increased activation across the frontal lobe, presupplementary motor area, increased frontal theta power during joint position sense and force matching tasks and increased cognition/attention during walking, jogging and landing support the behavioral data indicating increased neuropsychometric motor planning neural activity following ACL injury. Taken together, patients with ACL injuries may experience a loss of neural efficiency to engage in motor control, thereby contributing to both 1) impaired motor performance during dual-tasking or unanticipated movements and 2) an increased risk of secondary injury when attempting to rapidly increase motor complexity and environmental stimuli during early return to sport.25,63–66,80–82

SENSORY REWEIGHTING THERAPY

VISUAL PERTURBATION TRAINING

Functional navigation and interaction with the environment rely heavily upon continual integration of visual information.71,83,84 Visual information processing is further recruited for motor control following ACL injury, potentially due to sensory reweighting from the deafferentation of joint mechanoreceptors and/or the use of visually-dominated exercises and internal feedback to the injured joint during physical therapy.36,57,55–59 While patients may be able to compensate with increased visual processing for simple exercises, an inundation of dynamic visual information on the sporting field may overwhelm neural processing resources and the visually biased movement compensation strategy may become a re-injury risk liability. ACL rehabilitation efforts may consider incorporating complex sensory challenges, like visual perturbation, in order to simulate the dynamic sport environment that athletes will face once they leave the clinic.20,21,29,85–87

Stroboscopic glasses (SG) provide a novel approach to train visuomotor function by perturbing and reducing visual feedback.36 Typically, visual perturbation training has been limited to eyes open and eyes closed conditions with no progression between, but SG provides the ability to incrementally perturb visual information by increasing the duration of the opaque state (range: 25 to 900 msec) relative to the constant duration of the transparent state (100 msec).88 Originally designed to be a mobile sports training tool, SG has allowed researchers to investigate the effects of perturbed vision in context-specific environments.89 Early research with SG explored behavioral performance on motion coherence, divided attention, multiple-object tracking,90 short-term visual memory,91 and anticipation,92 as well as performance on sports-specific tasks from single-leg squatting,93 ice hockey,94 tennis,95 and badminton.96 These authors concluded visual perturbation training improves sport-specific behavioral performance and aspects of neurocognition including visual memory, anticipatory timing of moving visual stimuli, and central visual field motion sensitivity and transient attention ability.

SG simulates the dynamic visuomotor and cognitive/atentional demands of athletic activity while remaining in a controlled clinical environment.92,94,97,98 As patients with ACL injuries exhibit degraded motor control during drop-jump landing, cutting, and postural control under impaired visual conditions relative to normal vision,27,28,50,53–55,99,100 SG may facilitate increased proprioceptive integration in response to perturbed visuospatial information.36,89 ACL rehabilitation efforts that incorporate SG may be able to alter sensory weighting by decreasing the amount of visual information available to the athlete, thereby requiring the athlete to upregulate their use of remaining proprioceptive or vestibular inputs to guide movement. Utilizing SG in ACL rehabilitation may also enhance visuomotor processing efficiency in a compensatory manner to handle the increased reliance on vision to maintain low injury-risk biomechanics.48

MOTOR LEARNING PRINCIPLES

A key limitation of ACL rehabilitation is the inability to facilitate the acquisition of injury-resistant motor patterns that persist beyond the clinic.101 This limitation likely contributes to high rates of secondary injury and long-term pathologic sequelae, such as aberrant joint loading and early-onset osteoarthritis.102 The incorporation of motor learning principles may facilitate the acquisition of lasting, injury-resistant movement patterns that persist beyond the clinic and into the field,103 since these principles can facilitate neuroplasticity in cortical regions dedicated to movement.104,105 Specifically, the use of an external focus of attention and implicit learning may serve an adjunctive role
to sensory reweighting therapy. An external visual focus of attention can ensure visuospatial demands during training and implicit learning can reduce the cognitive demands for motor control to potentially enhance training.37–40

I. MODIFIED EXTERNAL FOCUS OF ATTENTION FOR VISUOSPATIAL ATTENTION

While the classic definition of external focus (EF) feedback is purely an attentional manipulation, this clinical commentary modified the traditional EF framework to push attentional focus toward the external visuospatial environment. ACL therapy that employs a visual EF can simulate real-world training scenarios that better prepare athletes for return to activity when visual attention is focused on the environment and not the body. Training with EF prioritizes the movement goal or the movement’s effect on the environment, rather than an internal focus (IF) on the movement or body segment itself.106 For example, a therapist who directs patients to balance a light-weight bar horizontally with their outstretched arm while performing a single-leg balance task employs visual EF.37,107 In contrast, a therapist who directs patients to actively attend to their ankle, knee and hip alignment while balancing employs IF, which is the predominant strategy in ACL therapy. An IF approach to therapy may hinder the translational benefits of rehabilitation, as humans typically navigate the world with a visual EF on the environment (e.g., running to a ball) – not on their moving joints or mechanics.108

The Constrained Action Hypothesis posits conscious (cortical) awareness of movement constrains the automatic, subcortical processes that would otherwise facilitate movement.109 By training with EF, one may relieve the attentional demands on the cortex by shifting motor control to subcortical regions and enhance motor learning and performance relative to training with IF.102,110–113 Behaviorally, training with EF improves agility performance,57 increases jump height,114 and promotes safer landing patterns during a single-leg hop for distance task in patients with ACL-R compared to performance with IF.115 Additionally, engaging in EF increases time to failure, reduces ratings of perceived exertion,116,117 and increases movement efficiency potentially by reducing unnecessary muscle contributions by modulating the inhibitory mechanisms within the primary motor cortex.117,118

II. IMPLICIT LEARNING

Developmentally, humans learn to move through observation and implicit trial-and-error (e.g., learning to ride a bike, walk, throw).119 Implicit feedback facilitates motor learning without explicit, declarative instructions or cuing,37 thereby increasing neural efficiency by reducing the attentional demands to engage in complex movement. While explicit cuing engages cognitive processes (frontoparietal regions), implicit cuing facilitates more direct sensorimotor activity.120 Further, training with implicit cuing has recently been associated with motor cortex reorganization, potentially supporting more efficient premotor or cortical interneuron processes.121 While few studies have examined the behavioral impacts of implicit cues for sports medicine, Popovic et al. demonstrated improved landing biomechanics with implicit feedback relative to explicit/no feedback.40 Thus, instructional language informed by implicit learning may augment visual perturbation training by modulating sensorimotor neural activity and potentially increasing neural efficiency by reducing the cognitive load of learning injury-resistant movement strategies. The newly freed cortical resources may enable athletes to more readily attend to visual distractors during high-level sport (e.g., the ball, opponents) while maintaining neuromuscular control.37,122

For example, consider the scenario where a therapist trains an athlete with an ACL injury to land correctly after a drop vertical jump. A therapist may opt to follow an explicit learning model and inform the athlete of all the biomechanical variables he or she is evaluating (e.g., trunk flexion, knee flexion, knee valgus, foot rotation, etc.). This type of learning requires the athlete to attend to multiple aspects of his or her landing mechanics, thereby occupying a substantial amount of his or her cognitive resources. However, a therapist who opts-in to implicit learning may instead provide metaphorical instructional language (e.g., "land like a feather") and simple "yes/no" or "good/bad" feedback to train the athlete to land. This trial-and-error method may augment visual perturbation training by alleviating the burden of attending to biomechanical variables, thereby freeing the athlete’s cognitive resources to attend to external visual stimuli without compromising their neuromuscular control.

CLINICAL APPLICATION

Future studies are needed to explore the therapeutic efficacy of combining SG and motor learning principles (i.e., EF, implicit learning) with traditional therapeutic exercises during ACL rehabilitation. A barrier to such studies is a lack of clearly defined and easily replicable exercises that combine these novel modalities. This clinical commentary details ways therapists and researchers can supplement the current standard of care by adding SG and motor learning principles to agility, balance and plyometric exercises in novel ways. Provided are example exercises with specific instructional language and visual targets (Table 1). Further clinical examples of EF and implicit learning can be found in the work of Gokeler et al.37 An error scoring system with detailed criteria to assess behavioral performance while wearing SG is provided as well (Table 2).

AGILITY DRILLS

(i) The T-test requires the athlete to run 10 m to tap a cone, cut to the right or left for 5 m to tap another cone, cut to the opposite direction for 10 m to tap the third cone, return to the center by cutting 5 m to tap the first cone and then run 10 m back to the start position - thereby running in a “T” formation (Figure 1A). A modification that increases the difficulty of this task and simulates the cognitive demands of sport is to have the clinician call out “Left” or “Right” to indicate which direction the athlete should cut prior to reaching the first cone, thereby creating an unanticipated cutting task which has been previously associated
Table 1: Instrumentation and Instruction to Facilitate Perception-Action that Employs Visual External Focus and Implicit Learning Principles.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Visual Cues</th>
<th>Implicit Cues</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-test</td>
<td>Tap the cones</td>
<td>&quot;Run as fast as a cheetah&quot;</td>
</tr>
<tr>
<td>Agility Ladder Drills</td>
<td>The confines of the ladder</td>
<td>&quot;The floor is as hot as lava&quot;</td>
</tr>
<tr>
<td>Single-leg Deadlifts</td>
<td>Place an object by the cone(s)</td>
<td>&quot;Flow like water&quot;</td>
</tr>
<tr>
<td>Single-leg Stance (on foam)</td>
<td>Hold the bar horizontally</td>
<td>&quot;Be steady as a rock&quot;</td>
</tr>
<tr>
<td>Vertical Jumps</td>
<td>Hit the overhead target</td>
<td>&quot;Explode like a volcano&quot;</td>
</tr>
<tr>
<td>Squat Jumps</td>
<td>Land facing the cones</td>
<td>&quot;Jump like a kangaroo&quot;</td>
</tr>
</tbody>
</table>

Table 2: Error Scoring System Used to Assess Behavioral Performance.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Error Count</th>
</tr>
</thead>
</table>
| T-test                        | 1. Miss a cone  
                                | 2. Cut to the wrong direction                  |
| Agility Ladder Drills         | 1. Hit the ladder  
                                | 2. Incorrect foot placement                    |
| Single-leg Deadlifts          | 1. Opposite foot touches ground  
                                | 2. Either hand touches ground  
                                | 3. Object placed in wrong location             |
| Single-leg Stance (on foam)   | 1. Opposite foot touches ground  
                                | 2. Either hand touches ground                  |
| Vertical Jumps                | 1. Miss the target  
                                | 2. Land on wrong foot                          |
| Squat Jumps                   | 1. Land facing wrong orientation                 |

with increased injury-risk biomechanics compared to anticipated trials. (2) Agility ladder drills require athletes to match specified foot-placement patterns within the context of an agility ladder (Figure 1B).

**BALANCE**

(1) Single-leg deadlifts may be modified by requiring athletes to gently place a small object on the ground next to a cone target (Figure 1C). To increase the difficulty, multiple cones can be placed at different angles within the athlete’s field-of-view, set at distances equal to his or her max volitional reaching distance while standing on one leg. For example, if the clinician chooses to use three targets, then he or she may call out "Left," "Center," or "Right" to vary the task order and difficulty. (2) Single-leg stance on a foam surface may be modified by having the participant hold a light-weight bar with an outstretched arm and focus on keeping it steadily horizontal (Figure 1D).

**PLYOMETRICS**

(1) The VERTEC is a therapeutic tool that assesses maximum vertical jump height by requiring athletes to jump and hit an overhead target (Figure 1E). While using the VERTEC to have athletes hit a mark equal to 80% of their maximal jump height, clinicians may call out "Left" or "Right" during the initial flight phase of the jump to signal to the athlete to unilaterally land on his or her left or right leg. The use of spontaneous cuing creates an unanticipated landing task, which has been previously associated with increased injury-risk biomechanics compared to anticipated landing. (2) Jump squats may be modified by placing four cones around the participant at 0, 90, 180 and 270 degree positions (Figure 1F). After numbering each cone one through four, the clinician may then rapidly call out cues to the athlete to specify which cone they should face after each jump squat. To increase the difficulty of this cognitive challenge, the clinician can introduce more cones or increase the rapidity of cuing.
Clinicians should first verify their athlete can perform all exercises successfully before incorporating SG. Then clinicians may expose their athlete to SG by beginning at the easiest difficulty level (highest frequency of fluctuation between transparent and opaque states). As their athlete improves performance behaviorally, clinicians may increase SG difficulty to increase the visual-cognitive demand.

In addition to the provided Error Scoring System (Table 2), clinicians may use the NASA Task Load Index questionnaire or Borg’s Rating of Perceived Exertion scale to optimize the SG difficulty level during training. These tools allow clinicians to assess an athlete’s perceived level of difficulty performing exercises with SG. For example, if clinicians want to simulate “hard/difficult” sports scenarios with SG, but their athlete rates his or her experience as “moderate,” clinicians may increase the visual perturbation by raising the SG difficulty level.

Alternatively, clinicians may opt to only incorporate SG into exercises that are below their athlete’s current physical capability initially. For example, if an athlete only recently performed a single-leg hop successfully, their clinician may choose to perturbate a single-leg balance exercise by adding SG. After successful completion of the single-leg balance exercise with SG, the clinician may then choose to advance the athlete’s training by incorporating SG into the harder single-leg hop task. This style of initially incorporating perturbations into exercises that are below a patient’s current physical capability is common in rehabilitation.

CONCLUSION

A novel approach to ACL rehabilitation that incorporates sensory reweighting therapy may shift neural processing toward proprioception and reduce the dependency on vision for motor control and/or increase visuomotor efficiency. ACL rehabilitation efforts that incorporate visual-perturbation training supplemented by motor learning principles (visual EF and implicit learning) may fill this gap. Future studies are needed to evaluate the therapeutic efficacy of sensory reweighting therapy in ACL rehabilitation.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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Incorporating Internal and External Training Load Measurements in Clinical Decision Making After ACL Reconstruction: A Clinical Commentary

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Background and Purpose
Poor outcomes after anterior cruciate ligament reconstruction (ACLr), including the relatively high risk of suffering a subsequent ACL injury, suggest the need to optimize rehabilitation and return-to-sport testing. The purpose of this commentary is to introduce clinicians to the concept of monitoring training load during rehabilitation, to review methods of quantifying internal and external loads, and to suggest ways that these technologies can be incorporated into rehabilitation progressions and return-to-sport decisions after anterior ACLr.

Description of Topic with Related Evidence
Quantifying and identifying the effects of training load variables, external (distance, impacts, decelerations) and internal (heart rate, heart rate variability) workload, during rehabilitation can indicate both positive (improved physical, physiological, or psychological capacity) or negative (heightened risk for injury or illness) adaptations and allow for the ideal progression of exercise prescription. When used during return-to-sport testing, wearable technology can provide robust measures of movement quality, readiness, and asymmetry not identified during performance-based testing.

Discussion / Relation to Clinical Practice
Researchers have reported the actual in-game demands of men and women of various ages and competition levels during multi-directional sport. Wearable technology can provide similar variables during rehabilitation, home exercise programs, and during on-field transition back to sport to ensure patients have met the expected fitness capacity of their sport. Additionally, clinicians can use internal load measures to objectively monitor patient’s physiological responses to rehabilitation progressions and recovery rather than relying on subjective patient-reported data.

Level of Evidence
5

BACKGROUND AND PURPOSE
Anterior cruciate ligament (ACL) tears are common injuries in cutting and jumping sports that lead to subsequent psychological and physical ramifications, including an increased risk of early onset knee osteoarthritis. After injury, up to one-quarter of athletes that return to sport suffer a second ACL injury, 30% of which occur within the first 20 athletic exposures after their return. These alarming statistics highlight the need to optimize rehabilitation practices and return to sport decision making. Recovery from ACL injury involves 6-18 months of progressive rehabilitation before clearance from the medical team (i.e. surgeon, physical therapist) to return to sport. As athletes advance through rehabilitation, their progress is often tracked by the increases of repetitions, duration, in-
tensity and the complexity of exercise. At a time when neuromuscular function (i.e. strength, coordination, functional performance) has returned to near pre-injury levels and the time since surgery ensures optimal physiologic healing of tissue, the sports medicine team (i.e. surgeon, physiotherapist, etc.) performs return-to-sport testing procedures to gauge an athlete’s readiness to perform and risk of subsequent injury. Tests and measures that are included in these return-to-sport decisions are controversial and inconsistent, but generally include clinically-based procedures that identify residual asymmetry in strength, function, and power through isometric or isokinetic strength and single-leg hopping tests. Many of the current return to sport procedures are performed in controlled, clinical environments and may not elucidate an athlete’s true performance or injury risk during the required demands of their sport.

Monitoring training load in an athlete's natural environment has received a lot of attention in recent literature as emerging evidence indicates a relationship between load and injury. Training load is typically categorized into either external or internal workload, with external workload capturing the mechanical work done by an athlete and internal workload referring to the physiological and psychological stress imposed by the training session on the athlete. Example measures of external workload include total distance travelled, the frequency of accelerations, decelerations or changes in direction, and the number of jumps performed over the course of a training or competitive session. Internal workloads can include the perception of effort in the form of ratings of perceived exertion (RPE) or physiological responses like duration of a training session spent in a specific heart rate interval, and resting heart rate variability (HRV). Quantifying and identifying the effects of these training load variables is crucial because they can indicate both positive (improved physical, physiological, or psychological capacity) or negative (heightened risk for injury or illness) adaptations. Training load measures are becoming more accessible to clinicians and coaches because they can be quantified using wearable technology or handheld devices. Instrumentation that contains global positioning system (GPS) units, accelerometers, force measuring insoles, and/or heart rate monitors are being used to quantify internal and external load variables with accuracy and precision.

Workload monitoring and management has not caught on in anterior cruciate ligament reconstruction (ACLr) rehabilitation practices or return-to-sport decision making, potentially due to perceptions that measurement tools are too expensive, or analyses are too time consuming. However, workload metrics can provide valuable data for clinicians during rehabilitation procedures. While using measures like repetitions and intensity can help clinicians progress individual exercises, this method fails to offer a holistic view of the training load encountered by the athlete. Likewise, current return-to-sport decision making does not factor in training load variables that may better elucidate an athlete’s readiness to participate in sports with high multi-directional demands that often are not paralleled during rehabilitation sessions. The high rate of second ACL injury, especially within the first 20 exposures after return to sport, suggests that there is room for improvement in returning an athlete to sport, including current rehabilitation practices and return-to-sport decision making processes. The purpose of this commentary is to introduce clinicians to the concept of monitoring training load during rehabilitation, to review methods of quantifying internal and external loads, and to suggest ways that these technologies can be incorporated into rehabilitation progressions and return-to-sport decisions after ACLr.

**TRAINING LOAD MONITORING**

**EXTERNAL WORKLOAD**

Clinicians often monitor external workload during rehabilitation in the form of training volume, traditionally logged as a combination of the frequency (number of sets and repetitions or exercise duration) and intensity (weight or resistance) of the prescribed therapeutic exercises. While these traditional external workload variables are important to monitor, they are limited in scope because they do not encompass the complexity of exercise, nor do they provide a global and comprehensive view of the patient’s external workload. Total training duration may give a more comprehensive view of athlete workload but does not include any measures of intensity or quality of movement that could significantly alter an athlete’s response to the treatment session. To more accurately quantify external workload, clinicians may consider the use of wearable technology, such as activity monitors, accelerometers, or force measuring insoles.

**DISTANCE MEASUREMENTS**

Activity monitors (AM) that measure physical activity (steps per day) are gaining popularity in certain clinical populations. Clinicians and researchers have used AM in various ways, including assessing the effectiveness of cardiac rehabilitation and other behavioral interventions. Additionally, AM have been used to quantify activity in populations such as children with cerebral palsy and adults after stroke, and have been used in rehabilitation settings like skilled nursing facilities and inpatient rehabilitation to gauge the intensity of exercises and patient participation during treatment sessions. AM vary depending on the manufacturer and model but are often worn at waist-level or on the distal aspect of the arm or leg. These devices combine data from an embedded tri-axial accelerometer with a proprietary algorithm to measure step counts and calculate distance as a function of step count and step length. Off-the-shelf AM (i.e. FitBit) are generally reliable for tracking step counts and distances, while research- and clinical-grade AM instrumentation (i.e. ActiGraph) can provide more reliable spatiotemporal variables than commercially-available AM during both walking and running, including step counts and distances and the duration of any bouts of active or sedentary time when worn for an extended period. Though a few studies have reported using AM to measure physical activity in youth sports, the use of AM has yet to gain traction in sports medicine settings because of time and cost perceptions.

Global positioning systems (GPS) are becoming more common in team sports, especially for tracking distances...
traveled by players during practices and games. Since GPS technology can accurately pinpoint one’s location using a series of orbiting satellites, GPS units calculate distances travelled based on changes in location. Activity monitors and/or GPS units can be a cost-effective complement to traditional external workload measures during rehabilitation and return-to-sport after ACLr. There is emerging evidence reporting average sport-specific loads that can provide guidelines to prepare athletes to return to their sport. For example, elite soccer players travel an average of over 10,000 meters, whereas basketball players travel 6,000-7,000 meters per contest. Clinicians should ensure that athletes have built the requisite fitness base and have received adequate exposure to similarly matched load intensities for safe return to their sport. Most published data are based on game data, but sport practices have the potential for greater intensity and larger distances traveled, which may need to be accounted for in rehabilitation. Not quantifying rehabilitation sessions or monitoring an athlete outside of the rehabilitation setting could result in the clearance of an athlete for return to sport from strength and symmetry measures without evidence that the athlete is prepared to tolerate the expected workload when released to compete. This could happen in a traditional rehabilitation setting, or with an independent strength and conditioning professional. Regardless, the clinician that ultimately makes the return to sport decision needs to be knowledgeable of these data. In addition to providing valuable information for clinicians, AM or GPS units can also be used to help with exercise prescription outside of the clinical setting. It may be unrealistic for an athlete to simulate 10,000+ meters in a rehabilitation setting; however, using this wearable technology, clinicians can prescribe progressive distances as part of a home exercise program. Traditionally, this is done with straight line running distance because of the ease of measurement, but most sports require multi-directional movements that can be quantified in real-time with AM or GPS units.

EXAMPLE APPLICATION DURING REHABILITATION AND RETURN-TO-SPORT TESTING

Figure 1 depicts an ideal theoretical rehabilitation management model for an athlete after ACLr. This model should be individualized to the athlete and could be uni- or multivariate, depending on the sport’s activity demands. For this example, consider total distance covered as measured by an activity monitor. When monitoring these variables after ACLr, clinicians should account for both dedicated rehabilitation workload (whether performed in a clinical setting or as a home exercise program) and other physical activity. When progressing distance workload, clinicians must rely on their experience, physiological healing of the tissue, the patient’s response to treatment (potentially including internal load measures as described later in this review), and the patient’s goals (including sport-specific demands). The model shows a total daily distance spike (time of rapid increase in distance) around two-weeks post-operative when gait and functional workload begin to normalize and pain decreases, and around 12-weeks which is the typical time of initiating a jogging/running program post-ACLr if certain criterion are met. Similarly, the model shows a disturbance spike in dedicated rehabilitation distance around week 12. There is then a steady progression of distance during rehabilitation to reach average and maximal sport demands, though the pace of progression slows to stabilize the acute-to-chronic workload ratio. Monitoring these variables elucidates the athlete’s fitness capacity for clinicians and can be used as comparisons to previously published values specific to the patient’s age, sex, competitive level, and sport during the return-to-sport decision making process. The goal is that the athlete has the capacity to load at average and maximal game demands before being fully cleared to return-to-sport. While research is needed to validate this model, it helps illustrate the potential interaction of daily and rehabilitation workload and shows how to incorporate activity demands as specific and meaningful long-term goals during rehabilitation progressions.

GROUND REACTION FORCE

Ground reaction forces can help clinicians quantify magnitudes and asymmetries of limb loading. In laboratory settings, force platforms can provide 3D analysis of ground reaction forces but are expensive and not accessible to most clinicians. Force measuring insoles (i.e. loadcell®, Novel Electronics, St. Paul, MN) can provide valid and reliable asymmetry data during squatting, running, and landing. Force measures using portable insoles have been reported to be highly correlated with knee extension moment asymmetries during landing, a common finding in individuals after ACLr that may be predictive of a subsequent injury. In addition to their prognostic value, these data can be used throughout the rehabilitation process to provide biofeedback to patients to improve neuromuscular control (i.e. increase or reduce forces) and normalize movement between the reconstructed and unaffected limbs. The assessment of limb loading asymmetry can be a valuable contribution during both early-stage rehabilitation as the athlete attempts to regain symmetry with controlled movements like gait and squatting, and in late-stage rehabilitation when determining return-to-sport readiness. Using force measuring insoles during return-to-sport testing allows clinicians to assess movement quality differences between the reconstructed limb and healthy limb. Accelerometers measuring tibial acceleration can also be used as a surrogate measure for ground impact and can be easily used in controlled clinical or natural playing environments.

EXAMPLE APPLICATION DURING REHABILITATION AND RETURN-TO-SPORT TESTING

During early post-operative rehabilitation, a patient’s ground reaction force can be displayed during a variety of two-legged squatting progressions or other activities. This biofeedback allows the patient to correct asymmetry in real-time using an external focus. The goal in the early-phase would be to regain symmetry by weight-shifting towards the reconstructed limb. During later-stage rehabilitation, clinicians may use a similar approach to overload the reconstructed limb for preparation of asymmetries that would occur during sport.

Ground reaction forces can also be utilized during single-
leg activities both during rehabilitation and return-to-sport testing. Figure 2 shows the vertical ground reaction force curves during gait of a patient after ACLr at post-operative weeks 12 and 31. At week 12, impact peaks and loading rates at heel strike appear relatively symmetrical, yet the patient produces significantly less ground reaction force during push off in the reconstructed limb. At week 31, the patient is loading the reconstructed limb at higher levels than the non-injured limb. While other contextual factors should be accounted for, alone these graphs show a significant positive progression in the patient’s confidence in and function of the reconstructed limb.

MULTI-DIRECTIONAL MOVEMENTS

Deceleration is a primary mechanism of lower extremity injury and non-contact ACL rupture. A vast majority of ACL injuries occur during decelerations associated with cutting (horizontal change in direction) and landing (vertical change in direction). During rehabilitation, clinicians must simulate sport-specific game demands and emphasize both the quality (movement patterns) and quantity (frequency) of accelerations and decelerations before returning to play.

Cutting is a necessary component of a rehabilitation plan for patients that participate in sports like soccer, which demands up to 700 cuts per game. An accelerometer can measure the quantity and intensity of simulated cuts during rehabilitation, home exercise programs, and return-to-sport testing procedures. Current clinical tests of agility provide time measures for the completion of a test, but to the authors’ knowledge, there are no clinically accessible agility measures that identify asymmetries, and thus may not fit in the return-to-sport testing battery. Being able to quantify accelerations and decelerations during procedures like the T-test (Figure 3), pro-agility, and lower extremity functional test (LEFT) may provide crucial information about an athlete’s ability to create power and speed on an individual limb during a functional activity.

Like cutting, jumping and landing require repetitive demands (> 50 jumps per volleyball and basketball match), making it essential to monitor jump frequency and landing force in athletes rehabilitating from ACLr. Commercial accelerometers worn at waist-level can track an athlete’s jump count, jump height, and landing. Much like total distance and cutting, clinicians should have an appreciation for the sport-specific demands of their athlete upon return to sport and ensure that their rehabilitation plan adequately prepares the athlete for safe return. Jump count may not be as critically under-prescribed as others measures during rehabilitation because of the relatively common use of plyometric activities in ACL rehab programs; however, these plyometric programs need to be implemented and progressed in a safe manner. Accelerometers that record jump count can be used to monitor and progress plyometric training loads during rehabilitation (e.g. VERT wearable jump monitor, Mayfonk Athletic, Fort Lauderdale, FL). Real-time jump height measurements can also be a valuable performance variable to monitor during rehabilitation. Jump height can help quantify the intensity of an exercise during an individual rehabilitation session or ensure that an athlete’s performance progresses appropriately during early stages of rehabilitation and does not decline as other load factors increase in preparation for return-to-sport.

EXAMPLE APPLICATION DURING REHABILITATION AND RETURN-TO-SPORT TESTING

Figure 4 shows the progression of accelerometer measured...
jump count throughout post-operative rehabilitation for an adolescent, competitive, female soccer player. Similar to progressing distance workloads in rehabilitation, clinicians must rely on their experience, physiological healing of the tissue, the patient’s response to treatment, and the patient’s goals. In this example, jump count shows a substantial increase throughout weeks 13-23 as the patient participates in progressive plyometric training to improve strength, power, speed and athletic function. Then, knowing that the patient’s goal is to return to soccer, exercise prescription transitions away from jumping to cutting and other horizontal agility exercises and drills to match the

Figure 2: Example vertical ground reaction curves during gait of a patient after ACLr at post-operative week 12 and week 31.

Figure 3: Example use of accelerometry during agility t-test.
demands of soccer. An athlete that participates in a more jump-dominant sport like basketball or volleyball may benefit from a more sustained frequency level of high jumps, or in the case of a volleyball setter may need to increase towards >200 submaximal jumps to meet the demands of the sport.

**INTERNAL LOAD**

A holistic consideration of training load in rehabilitation progressions should include measures of both external and internal stressors. Common factors that contribute to the overall physical, physiological, and psychological loading on the system include elements such as travel, academic demands, non-sport stressors, sleep, nutrition, and subjective wellbeing. Although it is impossible for a single measure to quantify the interactions of numerous variables on an athlete’s adaptation to load, monitoring internal workload can complement current ACLr rehabilitation procedures.

**RATING OF PERCEIVED EXERTION**

There are numerous non-invasive, time-effective options for quantifying internal load that are frequently used in athlete monitoring and could help guide the rehabilitation process. Session RPE (sRPE) is a cost and time effective option that measures an athlete’s perceived intensity of a training session. Immediately following a training session, the athlete provides a subjective report of the intensity of the session using a 10-item Borg’s CR10 scale. This number is multiplied by the total minutes of the training session to yield sRPE. sRPE has been strongly correlated with heart rate during steady state and high intensity exercise. In addition to its correlation with cardiorespiratory fitness, sRPE, when monitored and analyzed over time, demonstrates some promise as a predictor of injury when combined with measures of an athlete’s well-being.

A common criticism of sRPE is that this number may not accurately represent the intensity of a training or rehabilitation session. For example, when an athlete records a total daily training load of 180 arbitrary units, this value could indicate a near-maximal training session (RPE = 9) that was 20 minutes in duration or, an easy training session...
Heart rate (HR) has been used to monitor the influence of exercise load on the body. HR can quantify the body's tolerance to external stressors (e.g., exercise). When measured at rest, during, or immediately following exercise, HR measures may represent autonomic nervous system (ANS) control of the heart and provide sensitive indicators of the body's response to exercise load.

A critical aspect of rehabilitation is delivering the appropriate dose of an intervention to progress a patient towards targeted outcomes. While dosage is most frequently adjusted based on patient response (e.g., reported pain levels, changes in range of motion or movement pattern after a selected intervention), resting HR data can assist clinicians in providing more individualized intervention prescription. When monitored consistently over time, patterns in resting HR and heart rate variability (HRV) can reflect an athlete's physiological and psychological adaptation to and readiness for rehabilitation and other life stressors that influence a patient's trajectory to recovery (e.g., fatigue, sleep quality).

HRV is a measure that has attracted the attention of sport scientists, coaches, and clinicians due to its sensitivity as an index of athletes' physiological response to load. HRV is derived from the variations in time between the R-R intervals identified on an electrocardiogram trace (Figure 3). HRV represents the synchronization of the ANS and is an indirect measure of the dynamic coordination between the sympathetic and parasympathetic systems on the heart during stress and recovery. Resting HRV is predominantly controlled by parasympathetic, or vagal, tone and this has been previously confirmed by pharmacological blockade studies. HRV can provide a sensitive and accurate reflection of the body's physiological response to load, and therefore is an important measure to consider alongside rehabilitation protocols.

When assessed at the beginning of a training session, HRV can serve as a physiological readiness index with minimal resource burden and high potential to inform training load management methods for improved sport performance outcomes. HRV can be measured non-invasively and quickly (<60 seconds) with electrocardiogram, chest strap HR monitors or smartphone-based technologies. With technological advancements such as ring-based (e.g., Oura Ring, Oura, Oulu, Finland) and smartphone-based photoplethysmogram (PPG) acquisition, PPG-based HR monitoring is readily available and proving to be just as valid and reliable as heart rate strap measurements.

Recent investigations using HRV as an internal load measure demonstrate strong associations between changes in HRV and external training load. Athletes responding positively to training demonstrate increased HRV, reflecting an optimal functioning ANS. An organism expresses homeostasis through the adaptability and variability of the systems responding to stressors and maintaining overall health. In the case of the ANS, optimal homeostasis is represented by increased parasympathetic modulation at the heart. Rapid adjustments in heart rate can be made under increased parasympathetic control, allowing the body greater adaptability when responding to stressors or stimuli. Increased parasympathetic activity results in lower average heart rate and an increased variability of the time interval between each heartbeat (that is, an increase in HRV measures).

Conversely, reductions in HRV can be indicative of less parasympathetic modulation at the heart and in some cases, increased sympathetic nervous system control. This
imbalance of the ANS is reflected in heightened average heart rate, which leads to decreased variability of the time interval between each heartbeat and decreased HRV measures. Reductions in resting HRV have been researched as a physiologic marker of negative consequences in athletes diagnosed with overtraining syndrome who demonstrate long-term decrements in performance along with physiological and/or psychological signs and symptoms that resemble disturbed ANS function (e.g. excessive fatigue, altered sleep, depression). The uses of HRV in sport performance provide pragmatic examples of how monitoring patterns of change in a surrogate health measure like HRV can inform our understanding of risk profiles for overloading or perhaps underloading our athletes. Studying HRV patterns in response to rehabilitation and other non-training stressors provides useful information related to how the function of the ANS influences recovery after loading of somatic tissues.

**SUMMARY AND CONCLUSIONS**

Most ACL rehabilitation protocols and guidelines have shifted from time-based to criterion-based progressions to allow for individualization of rehabilitation and may help reduce the risk of under- or over-loading. The authors suggest adding parameters to these guidelines that incorporate internal and external workload measurements. For example, using normative sport demands as goals or thresholds during rehabilitation may help reduce under-loading that may occur during rehabilitation and ensure that the athlete has built up the requisite fitness to return to their sport. Further, close monitoring of variables like distance and jump count can promote more systematic exercise progressions and may decrease the risk of injury (e.g. patellar tendinopathy) from repetitive overuse or under-recovery.

While monitoring and progressing external workload during rehabilitation, internal workload can help clinicians justify their rate of progression. The application of im-

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**Figure 5**: Heart rate variability analysis. After proper identification of RR intervals from electrocardiogram trace (top picture), the measured time of each RR interval is plotted over time (middle picture). From the selected RR series, three common methods of HRV analysis can be performed: time domain, nonlinear and frequency domain (three bottom pictures).
Figure 6: Current factors (solid line) and factors newly available to easily measure (dotted line) that may affect the return-to-sport decision making process after ACLr.

Proven research methodologies in recent studies is revealing increasingly consistent directional changes of parasympathetic-mediated markers of HRV in response to athletes’ positive adaptations to training.\(^8\) Together, this evidence supports the previously-established hypothesis that, in general, athletes who exhibit an increase in parasympathetic-mediated HRV measures in response to training load are coping positively, performing optimally in their sport, and perhaps are at less risk of injury.\(^59,73,80,82\)

During return-to-sport testing and decision making, current best practice utilizes a combination of clinical examination (pain, effusion, laxity), single-leg hop symmetry tests, single-leg isokinetic strength symmetry tests, and functional or psychological self-report questionnaires to gauge an athlete’s readiness to return-to-sport.\(^81\) Other measures of external workload, including activity demands and limb loading symmetry during sport-specific activities may help complement the aforementioned testing battery (Figure 6). Athletes need to have the requisite physiologic readiness levels to safely return to sport. Clinicians can now monitor their athletes’ activity demands to ensure they are at a level commensurate with their sport. Using wearable technology, clinicians can gather robust information on limb loading symmetry. Forces that occur during sport-specific movements like landing and cutting represent movement quality measures that may not be perceived without technology. After ACLr, athletes should not be allowed to return to their sport unless the athlete is able to withstand external and internal workloads without deterioration of biomechanics or significant fatigue.

Measures of external and internal workload may provide important complementary information to clinicians involved in any stage of rehabilitation or the return to sport decision making process after ACL reconstruction. Wearable technologies are becoming increasingly more accessible, both in terms of cost and ease of use, and the data they provide can help quantify rehabilitation progressions, serve as comparisons for established sport-specific workload demands, and identify the athlete’s physiological well-being.

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29. Renner KE, Williams DSB, Queen RM. The reliability and validity of the loadsol(ri) under various walking and running conditions. *Sensors (Basel).* 2019;19(2). doi:10.3390/s19020265


In-pool return to swim protocols have been described for swimmers returning from being deactivated from swimming due to a shoulder injury who have full shoulder strength. Many swimmers actively participate in swim practice and competition with shoulder pain and experience deficits in performance. There are multiple reported risk factors associated with shoulder pain among swimmers, including training errors and physical impairments. These include pool and dry-land training errors, weakness in the scapular stabilizers and rotator cuff, and muscle tightness. A need exists for dry-land rehabilitation programs for impairments common to swimmers that can be performed in a traditional outpatient physical therapy setting. The purpose of this clinical commentary is to present a protocol using neuromuscular electrical stimulation (NMES), taping, strengthening, and stretching to address impairments that are common among swimmers while allowing continued active participation in practice and competition.

Level of Evidence
Level 5

BACKGROUND AND PURPOSE
Given the high shoulder injury rates of competitive swimmers, return to swim protocols (RTSP) can provide guidance to coaches and those involved in the rehabilitation of these athletes. Two RTSP have been previously described. Both provide excellent guidelines for training progressions based on shoulder symptoms during and after a workout. 1,2 Hamman’s 1 protocol provides guidance for swimmers who have been deactivated from swimming for more than six weeks and less than six weeks. This program is structured using a unique graded loading scheme of distance and interval time-based training. This system permits individualization of training based on a swimmers’ current training speed but requires that the swimmer be able to perform individual intervals during their practice. This may not be feasible if the swimmer has multiple teammates per lane training on uniform time intervals. Spigelman et al 2 provide an overview of swimming terminology, tools, drills, as well as a swimming volume and training-based RTSP which incorporates gradual loading of the shoulder. However, the criteria for beginning the RTSP require the shoulder to be nearly pain-free and the strength of scapular and glenohumeral muscles to be 5/5. Initiating this RTSP proves challenging given that competitive swimmers seeking care often present with substantial shoulder pain and impairments such as trapezius weakness. 3 These factors disqualify an individual from beginning this protocol and clinicians are left without guidance on progressing this group of patients to meet the criteria required to begin the RTSP safely. Additionally, the protocol from Spigelman et al 2 appears to be intended for swimmers who have undergone surgery or have been unable to train, as was the protocol described by Hamman. 1 Swimmers generally have less than optimal surgical outcomes for persistent shoulder pain associated with laxity, labral pathology and subacromial impingement. Montgomery et al reported that only 20% of swimmers returned to pre-surgery training volume after arthroscopic capsular plication and Brushoj et al found that only 56% of swimmers competed at their pre-injury level after shoulder surgeries that included debridement, bursectomies and partial coraco-acromial ligament releases. 4,5 Therefore, conservative management is preferred whenever possible. Many competitive swimmers that seek care for shoulder pain are currently having difficulty managing their training and report limitations in performance as well as activities of daily living. 3,6 Therefore, a need exists for management of swimmers who are currently training with shoulder pain. Those
with low to moderate pain that occurs only during and/or after swimming can usually be effectively managed with modifications to their swimming program and an accompanying comprehensive rehabilitation program. For swimmers with pain at rest and/or severe pain with normal ADLs such as grooming hair and carrying a backpack, a medical workup including imaging and removal from swimming participation are likely indicated. A rehabilitation program can then be implemented with gradual progression to in-water training. The purpose of this clinical commentary is to present a protocol using neuromuscular electrical stimulation (NMES), taping, strengthening, and stretching to address impairments that are common among swimmers while allowing continued active participation in practice and competition. This commentary will conclude with a case example describing the use of these guidelines for a competitive high school swimmer.

EXAMINATION AND IDENTIFICATION OF RISK FACTORS

Evaluation of a swimmer with shoulder pain includes a comprehensive history of the injury and identification of potential risk factors in the swimmers’ training. Several training errors among swimmers have been reported in the literature including: excessive swimming volume, lack of cross training, utilization of kicking drills that exacerbate shoulder symptoms, lack of a swimmer specific dryland program, and biomechanical errors in the swimming stroke.\textsuperscript{3,6–12} Table 1 describes these commonly reported training errors and modifications that can be implemented to reduce the adverse effects of these errors. Interventions should be chosen based on symptom irritability for which a classification system has been described extensively elsewhere by McClure et al.\textsuperscript{15} For competitive swimmers, this commentary will use high and low irritability classifications. History and exam findings in a swimmer with high irritability include pain \(\geq 4/10\) with swimming and pain with activities of daily living (ADL) and/or at rest. Interventions for these patients will initially focus on minimizing physical stress, activity modification, and addressing impairments in non-provocative positions. These patients may initially require rest from swimming if symptoms are constant and/or are of high intensity. A low irritability classification is used when pain is \(< 3/10\) with swimming, pain is minimal \(< 2/10\) with ADLs, and the patient is pain-free at rest. In these cases, interventions will address impairments and be designed to return swimmers to high functional demand.

Depending on irritability of a patient’s presentation, swimming volume, dryland program, cross training, and drills can be modified to appropriately reduce load on the painful shoulder(s) and address impairments contributing to the patient’s shoulder pain. Relevant impairments can be identified through a comprehensive physical shoulder evaluation. A thorough screening of the cervical spine is necessary, as swimmers frequently have a relevant cervical component to their shoulder pain and may benefit from use of a swimmers’ snorkel to reduce repetitive cervical rotation. An exam should also include evaluation of posture to identify any non-optimal postures including forward head or protracted scapula. Range of motion and muscle length assessments should include glenohumeral active and passive ranges of motion, pectoralis minor length, and latissimus dorsi length in addition to examination for posterior shoulder tightness using the Myers test.\textsuperscript{16} It is recommended that clinicians assess strength of the rotator cuff and scapular muscles with a handheld dynamometer which has good to excellent intra- and inter-rater reliability,\textsuperscript{17} has been found to be sensitive to detecting muscle strength changes over time,\textsuperscript{18} and provides valid and reliable assessment of

<table>
<thead>
<tr>
<th>Table 1: Identification and Management of risk factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Training Errors</strong></td>
</tr>
<tr>
<td>High swimming volume: Sein et al reported a 4-fold increase in shoulder tendinopathy in those swimming (&gt; 35,000)m/week so we consider (&gt; 35,000) as high swimming volume\textsuperscript{12}</td>
</tr>
<tr>
<td>Lack of cross training\textsuperscript{3}</td>
</tr>
<tr>
<td>Kicking drills with use of kickboard overhead or streamline position in swimmer with shoulder pain\textsuperscript{6,8}</td>
</tr>
<tr>
<td>Lack of specific dry land training or participation in a program involving repetitive overhead lifting (such as kettlebells) or lacking posterior shoulder/scapular/core strengthening\textsuperscript{7}</td>
</tr>
<tr>
<td>Stroke errors such as increased shoulder internal rotation or crossing midline at hand entry\textsuperscript{11}</td>
</tr>
</tbody>
</table>

Table 1: Identification and Management of risk factors
shoulder injuries and studies support scapular muscle and
neuromuscular

BACKGROUND

to greater angles of elevation in Phase 2. 

Emg activity of the middle trapezius, lower trapezius, infra-

prone T’s, Y’s, and ‘field goals’ (horizontal abduction with

resisted exercises for the scapula. Patients are progressed to 
begins with resisted retraction in neutral and manually re-
moved scapular assistance test26 as well as strength assess-
ment of the middle and lower trapezius and serratus ante-
rior to identify swimmers with scapular dysfunction. Table

2 presents the use of handheld dynamometry for muscle
strength testing as well as several special tests for core and
shoulder endurance and flexibility.

INTERVENTIONS TO ADDRESS IDENTIFIED
IMPAIRMENTS

A staged rehabilitation approach can be utilized to address
the impairments found on the examination. The authors'
approach will be described for typical impairments seen
among injured swimmers who continue to participate in full
or modified swim practices throughout the rehab program.
Others have described effective swimmer specific strengthen-
ing and stretching programs that address strength and
tissue length imbalances commonly found among swim-
mers.9,15 The aim of this commentary is to provide a brief
overview of a strengthening and stretching program fol-
lowed by a more intensive discussion of the NMES and tap-
ing protocols. Table 3 provides an overview of the strengthen-
ing and stretching program which includes scapular strengthen-
ing, shoulder neuromuscular re-education, ro-
tor cuff strengthening, core strengthening and inter-
ventions to address forward head and rounded shoulder pos-
ture. Manual techniques and stretching are used to address
posterior shoulder tightness, pectoralis minor/major and
latissimus dorsi tightness. Phase 1 scapular strengthening
begins with resisted retraction in neutral and manually re-
sisted exercises for the scapula. Patients are progressed to 
prone T’s, Y’s, and ‘field goals’ (horizontal abduction with 
external rotation) in Phase 2 as irritability of symptoms di-
nishes and these higher demand exercises can be per-
formed without pain. The Phase 2 exercises display high
EMG activity of the middle trapezius, lower trapezius, infras-
spinatus, teres major and supraspinatus.27 They are incor-
porated into the program to counteract the muscle imbal-
cances in swimmers that occur due to repetitive contraction
of the pectorals and internal rotators during the swimming
strokes.28 Using the same guideline, rotator cuff strength-
ing similarly begins in neutral in Phase 1 and progresses
to greater angles of elevation in Phase 2.29

BACKGROUND AND PROTOCOL FOR
NEUROMUSCULAR ELECTRICAL STIMULATION

Muscle weakness is a common finding in patients with
shoulder injuries and studies support scapular muscle and
posterior rotator cuff strengthening in the rehabilitation
of shoulder pain among competitive swimmers.9,15 Loss of
force production can result from muscle atrophy, fatigue,
tendon tears, and voluntary activation failure (VAF). Weak-
ness and VAF of the infraspinatus have been documented 
in healthy individuals with experimentally induced shoul-
der pain and shoulder fatigue.30,31 The addition of neu-omuscular electrical stimulation (NMES) to the quadriceps
muscle following knee surgery, after which VAF is a source
of weakness, results in faster gains in strength and function
when compared to traditional strengthening alone.32–34
Volitional muscle contractions sequentially recruit smaller
motor units and Type 1 fibers within a muscle followed by
large motor units and Type 2 fibers responsible for greater
force production if needed. Application of NMES results
in proportionally greater recruitment of large motor units
at lower force levels than volitional contractions alone.35
Therefore, it is likely that the mechanisms responsible
for faster strength gains with NMES compared to volitional
strengthening alone include direct recruitment of inhibited
motor units and greater recruitment of Type 2 fibers than
with voluntary contractions alone, resulting in greater force
production.32 Accordingly, it is reasonable to suggest that
clinicians may use NMES, as the protocol proposes, to more
efficiently improve shoulder strength versus use of tradi-
tional strengthening alone.

In addition to the peripheral strengthening effects of
NMES described above, there is evidence that changes in
brainstem cortex function with NMES can enhance motor
control.36,37 Cuesta-Gómez et al38 found that stimulation
of the interscapular musculature, deltoid, triceps, and wrist
extensors with a reaching task resulted in improved per-
formance of the task, by increasing active shoulder flexion
and elbow extension range of motion compared to use of
placebo stimulation. This study did not include any mea-
sure of cerebral cortex function; however, other researchers
found that cerebral cortex efficiency improved during motor
tasks following a short application of NMES with volition-
al activity in the upper extremity. This beneficial cerebral cor-
tex adaptation shows the potential to sustain improvements
in neuroplasticity and motor control with NMES.36 Another
study of 25 healthy subjects found that NMES with volun-
tary movement of the stimulated muscles increased corti-
cal excitability to a greater extent than voluntary movement
alone or NMES alone.37 This suggests that NMES may be
used simultaneously with a desired motor task to prompt
greater neuroplasticity than voluntary movement alone,
leading to greater improvements in motor control. Use of
NMES concurrently with a desired movement may be indi-
cated when a primary treatment goal is to improve motor
control. Therefore, the protocol for NMES contains guid-
ance to address motor control deficits of the shoulder, when
found, to stimulate neuroplasticity and improve neuromus-
cular control using the principles discussed in the above lit-

It is important to address altered neuromuscular control to restore optimal biomechanics at the shoulder
joint. Specifically, previous work supports promoting opti-
mal scapular biomechanics for improving strength via en-
hanced length-tension relationships of the deltoid and
other muscles which assist with shoulder elevation.39,40 It
may also provide a more stable proximal fixation for these
muscles and encourage erect thoracic posture while facilitating scapular posterior tilting and upward rotation.\textsuperscript{41}

Favorable changes in glenohumeral biomechanics have also been described with application of NMES to the lower trapezius and serratus anterior.\textsuperscript{42} Researchers applied NMES simultaneously to these muscles and demonstrated increased acromiohumeral distance in healthy young adults.\textsuperscript{42} Electrodes were placed over the lower trapezius muscle belly between the inferior angle of the scapula and the seventh thoracic spinous process. For the serratus anterior muscle, electrodes were placed at the intersection of the sixth rib and the midaxillary line. These findings provide evidence for a biomechanical mechanism whereby NMES may reduce subacromial pain by increasing the subacromial space. However, this study only used NMES in a static, nonfunctional position among healthy participants. To the authors’ knowledge, no studies exist on the application of NMES for neuromuscular re-education following shoulder injury in swimmers. The following section will present a protocol for NMES as an adjunct to traditional interventions for use in the treatment of shoulder pain in competitive swimmers.

The protocol (Table 4) includes applications of NMES for strengthening purposes and motor control, respectively. Phase 1 of the protocol begins with NMES applied to the middle and lower trapezius muscles with an isometric retraction contraction in a non-provocative position for those with high irritability. Once patients are pain-free with active horizontal abduction at 90 or 135 degrees of flexion in prone and weakness continues to be a primary concern, they are advanced to Phase 2a. This phase progresses to isotonic strengthening in more functional positions for swimmers as these positions are required for the recovery phase of the swimming stroke. If strength has improved in Phase 1 and/or 2a, but pain is still present with arm elevation, the authors perform symptom alteration tests to determine if the swimmer may have impairments in motor control. If pain with active shoulder elevation is significantly reduced or abolished with the modified scapular assistance test and/or if the swimmer has a positive Jobe empty can test in which pain is reduced or abolished with the scapula reposition test, the swimmer is advanced to Phase 2b. In Phase 2b NMES is used in conjunction with a specific task such as active shoulder elevation to improve motor control with this movement. If pain is reduced or eliminated or if active motion is improved with application of NMES in this manner, the authors consider this to indicate that impaired motor control is a contributing factor to the patient’s pain. In the authors’ clinical practice this finding suggests the clinician should proceed with use of NMES to the serratus anterior and mid/lower trapezius until the patient achieves pain-free active movement with carryover after NMES is removed. Carryover may occur rapidly or make take several sessions. If a desirable response is achieved with a simple task such as arm elevation, it is advised to progress to higher level activities such as performing resisted swimming strokes on a cable machine with light resistance. If a plateau is reached, NMES is discontinued and the patient is re-assessed to determine if other interventions are warranted.

**BACKGROUND AND IMPLEMENTATION OF TAPING**

Kinesiology and/or rigid taping are widely used techniques in the rehabilitation of shoulder injuries.\textsuperscript{43} There is an abundance of literature of varying quality on the use of taping as an adjunct to other physical therapy interventions; yet its effects remain inconclusive largely due to a lack of randomized placebo-controlled studies.\textsuperscript{43} Studies that demonstrate a positive effect on shoulder pain and function with taping propose that the mechanisms underlying these changes include: improved scapular positioning and enhancement of scapular kinematics,\textsuperscript{44–45} inhibition and/or facilitation of peri-scapular musculature,\textsuperscript{46–48} and improved shoulder joint proprioception and kinesthetic awareness/neuromuscular control.\textsuperscript{47} These mechanisms are relevant to the current topic given the previously discussed risk factors for shoulder pain among swimmers and the common impairments with which swimmers present. In this respect, taping may be a helpful adjunct to other physical therapy interventions for treating shoulder pain in swimmers. However, the inconclusive nature of the literature suggests caution is warranted with the use of tape in clinical practice. The authors therefore often perform a trial of taping and continue to use it only if there is an immediate improvement in pain or function.

In clinical practice, the authors primarily utilize a taping technique that mimics the scapula reposition test if this test is positive for pain reduction and the patient is unable to elevate their arm(s) or swim without pain. It is similar to the posterior scapular tilt technique outlined by Bdawai et al\textsuperscript{49} with some modification (Table 3). The tape is anchored, beginning at the anterior shoulder, inferior to the coracoid process and pull the tape over the upper trapezius muscle belly and continue posteriorly in an inferior and medial direction, covering the inferior angle of the scapula and crossing over the spine. This is performed bilaterally for symmetry. Clinicians may try kinesiology tape initially and if pain is abolished with active shoulder elevation and/or swimming strokes, may continue to use kinesiology tape. However, if kinesiology tape provides inadequate pain relief, rigid tape is recommended for greater support during daily activities only as rigid tape is too restrictive to be used while swimming. If no benefit is achieved with either technique, the rehabilitation process is continued as outlined above without using tape as an adjunct to treatment.

**CASE EXAMPLE**

**PATIENT HISTORY**

PK was a 15-year-old competitive swimmer, ranked in the top 25 in the country for his event with a goal of competing in college on scholarship. PK and his mother consented to data concerning his case being submitted for publication. He was referred to physical therapy with right shoulder pain that had been present for two months. Prior to experiencing shoulder pain, he had competed at nationals for the 200-yard backstroke, 100-yard freestyle and 100-yard breaststroke. His training regimen consisted of swimming an average of 5000 meters per practice six days a week. He
Table 4: Neuromuscular Electrical Stimulation (NMES)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Phase 1: Strength in non-provocative position</th>
<th>Phase 2a: Strength in functional position</th>
<th>Phase 2b: Motor Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indication</td>
<td>≥50% deficit in middle trapezius or lower trapezius strength as compared to contralateral side or bilateral weakness and pain with resisted horizontal abduction in prone or failure to improve with scapular strengthening without NMES</td>
<td>≥50% deficit in middle trapezius or lower trapezius strength and pain-free horizontal abduction in prone or failure to improve with scapular strengthening without use of NMES</td>
<td>Presence of a painful arc with a (+)modified scapular assistance test (defined as a 2 point pain reduction or increased elevation AROM) and/or (+)scapula reposition test (defined as a 2 point reduction in pain with Jobe empty can test) in the absence of significant trapezius or serratus anterior weakness</td>
</tr>
<tr>
<td>Patient Position</td>
<td>Standing or seated, shoulders neutral with isometric resisted scapular retraction using resistance bands</td>
<td>Prone T, Y or ‘field goal’</td>
<td>Standing with active shoulder elevation in flexion, scaption or abduction</td>
</tr>
<tr>
<td>Electrode Placement$^{41}$</td>
<td>Middle trapezius muscle belly</td>
<td>Middle trapezius/lower trapezius muscle belly</td>
<td>Lower trapezius muscle belly between the inferior angle of the scapula and the 7th thoracic spinous process. Serratus Anterior at the intersection of the 6th rib and the midaxillary line</td>
</tr>
<tr>
<td>Phase Duration</td>
<td>400μs</td>
<td>400μs</td>
<td>400μs</td>
</tr>
<tr>
<td>Pulse Frequency</td>
<td>75pps</td>
<td>75pps</td>
<td>25-55pps$^{37}$</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>1:5 (5 sec on, 25 sec off)</td>
<td>1:5 (5 sec on, 25 sec off)</td>
<td>1:3 progressing to 1:1 with 1 sec on and 1 sec off to be used with dryland stroke simulation actively or with resistance</td>
</tr>
</tbody>
</table>

did not have an accompanying dry land program. PK initially experienced pain at the superior aspect of the right shoulder while doing backstroke which progressively worsened until all strokes were painful. PK had been limited to
**Table 5: Comparison of outcomes at initial evaluation, progress evaluation and discharge**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Evaluation</th>
<th>Progress Evaluation (Week 4)</th>
<th>Discharge Evaluation (Week 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outcome Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPRS (0-10)</td>
<td>4 at present, 8 at worst while swimming</td>
<td>0 at present, 3 at worst while swimming</td>
<td>0 at present, 0 at worst</td>
</tr>
<tr>
<td>Quick DASH</td>
<td>29.5</td>
<td>9.1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Shoulder Range of Motion (degrees)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active flexion</td>
<td>R 162° L 178</td>
<td>R 179</td>
<td>R 179</td>
</tr>
<tr>
<td>Active abduction</td>
<td>R 155° L 170</td>
<td>R 170</td>
<td>R 170</td>
</tr>
<tr>
<td>Passive flexion</td>
<td>R 162° L 179</td>
<td>R 180</td>
<td>R 180</td>
</tr>
<tr>
<td>Passive abduction</td>
<td>R 155° L 190</td>
<td>R 190</td>
<td>R 190</td>
</tr>
<tr>
<td>Passive external rotation</td>
<td>R 80° L 95</td>
<td>R 95</td>
<td>R 95</td>
</tr>
<tr>
<td>Passive internal rotation</td>
<td>R 20° L 25</td>
<td>R 31</td>
<td>R 31</td>
</tr>
<tr>
<td><strong>Strength [kg of force as measured by MicroFet 2 hand-held dynamometer (Hoggan Scientific, Salt Lake City, UT)]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion at 90</td>
<td>R 8.1° L 16.3</td>
<td>R 13.6</td>
<td>R 15.9</td>
</tr>
<tr>
<td>Abduction neutral</td>
<td>R 12.7° L 16.3</td>
<td>R 24.1</td>
<td>R 25.4</td>
</tr>
<tr>
<td>External rotation prone</td>
<td>R 7.3° L 16.3</td>
<td>R 11.8</td>
<td>R 12.7</td>
</tr>
<tr>
<td>Internal rotation prone</td>
<td>R 9.1° L 17.3</td>
<td>R 15.4</td>
<td>R 18.2</td>
</tr>
<tr>
<td>Middle trapezius prone</td>
<td>R 4.5° L 5.4</td>
<td>R unknown</td>
<td>R 5.4</td>
</tr>
<tr>
<td>Lower Trapezius prone</td>
<td>R 3.6° L 5.0</td>
<td>R unknown</td>
<td>R 5.4</td>
</tr>
<tr>
<td>Posterior shoulder endurance test: isometric hold with 3lb weight at 145° horizontal abduction with thumb up (shoulder external rotation) in prone</td>
<td>R 10-sec L 35-sec</td>
<td>R 57-sec</td>
<td>R 71-sec L 68-sec</td>
</tr>
</tbody>
</table>

* indicates pain provoked with movement or test

kicking drills with a kickboard for two months as recommended by his coach. An MRI during that time revealed small anterior and posterior labral tears. PK tried a course of physical therapy at another clinic for one month which reportedly consisted of band exercises, stretches and interferential E-stim. Due to lack of progress with this program, PK was referred to the authors’ clinic to see an outpatient orthopedic physical therapist who specializes in treating swimmers.

EXAMINATION

PK’s evaluation was consistent with the MRI findings of labral tears [(+) dynamic shear test, and (+) crank test] in addition to presenting with signs of subacromial pain syndrome [(+) empty can test, (+) Hawkins-Kennedy test, and (+) painful arc] and anterior shoulder instability [(+) apprehension with (+) relocation test]. He also had positive scapula reposition and modified scapular assistance tests which may be indicative of impairments in scapular contribution to shoulder elevation. Pectoralis minor, latissimi dorsi and posterior shoulder tightness were also found. PK had reduced shoulder active and passive range of motion with empty end-feels. He had reduced glenohumeral and scapulothoracic strength in all planes compared to the contralateral shoulder *(Table 5)*. PK also reported pain with activities of daily living including lifting dishes into upper cabinets, reaching behind his back to dress and bathe, and sitting to type and write for school.

INTERVENTION AND OUTCOMES

PK was seen at an outpatient clinic for approximately 60-minute sessions, two times a week for eight weeks and was team-treated by the authors of this paper. *Table 6* outlines each week of PK’s treatment, including his subjective report, important interventions that were added, and upgrades made to his home exercise program. For the purposes of this commentary, these categories are included for only the first five weeks of his treatment as PK primarily made progressions in volume and resistance for the interventions outlined over the final three weeks. At PK’s first visit, he was advised to discontinue kicking with a kickboard overhead, a decision informed by McMaster et al who found that use of a kickboard increased shoulder symptoms in a group of swimmers with shoulder pain. Manual therapy techniques to improve soft tissue mobility and facilitate muscular control, scapular stability and strength were initiated at PK’s first visit. These were followed with targeted stretches and strengthening exercises for the scapular re-
Table 6: Example case progression over the course of care*

<table>
<thead>
<tr>
<th>Visit 1-2 (Week 1)</th>
<th>Visit 3-4 (Week 2)</th>
<th>Visit 5-6 (Week 3)</th>
<th>Visit 7-8 (Week 4)</th>
<th>Visit 9-10 (Week 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subjective</strong></td>
<td><strong>Interventions Added</strong></td>
<td><strong>Home Exercise &amp; Swimming Progressions</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Unable to stroke, only performing kicking drills | • NMES Phase 1  
• Scapula reposition taping  
• Scapular mobilizations and manually resisted exercise, rhythmic stabilization drills, instrument assisted soft tissue mobilization to posterior shoulder  
• Scapula retraction  
• Resisted shoulder ER, IR, extension  
• Pec minor stretch  
• Prone T’s and ‘field goal’  
• Core strengthening | • Scapula retraction, resisted shoulder ER, IR & extension with elastic band |
| *Patient was instructed in progressions in swimming yardage, intensity and frequency beginning with freestyle stroke using previously described soreness rules and progression guidelines based on the principles described by Spigelman et al.2 |
| Carryiing backpack for school still painful. | • Instructed parent in scapula reposition taping technique to perform prior to swim practice  
• NMES Phase 2a  
• Reverse step up with bilateral ER  
• Bilateral shoulder extension & squat row  
• Prone swimmers on swim ball  
• Modified sleeper stretch  
• Latissimi stretch | |
| No pain with swimming progression early in the week  
Pain with progression to no fins with parent taping | • Reviewed taping technique with parent  
• Resisted breaststroke and freestyle at cable column with number of strokes comparable to strokes completed in 50-yard swim | • Maintained |
| No pain with swimming progressions and no pain at swim meet | • Progressed to 90° abduction for resisted ER & IR with single leg stance  
• Plank with serratus plus maneuver  
• Advanced proprioceptive training  
• Progressed core strengthening  
• Lawnmower  
• High plank weight shifts on BOSU | • Progressed to 90° abduction for resisted ER & IR with single leg stance |
| No pain with swimming progressions, occasional pain with sitting at school early in the week, no pain with other ADLs | • Added lower extremity strengthening: Plyometric leg press, resisted standing 3-way hip exercise (hip flexion, abduction and extension) | • Maintained |

*Patient was instructed in progressions in swimming yardage, intensity and frequency beginning with freestyle stroke using previously described soreness rules and progression guidelines based on the principles described by Spigelman et al.2

Throughout his rehabilitation program, PK was instructed in progressions in swimming volume, intensity and frequency using previously described soreness rules and progression guidelines based on the principles described by Spigelman et al2 and Hamman.1 The authors also followed the National Athletic Trainer’s Association guideline recommending that youth athletes should progress distance

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or load in their specific sport by no more than 10% each week.\textsuperscript{14} Briefly, PK’s in water program was initiated with only the freestyle stroke, using scapular reposition taping (Table 3) and long blade swim fins. Zamparo et al\textsuperscript{50} found that the energy cost swimming with fins is 40% less than swimming without them. Given Morouço et al’s\textsuperscript{51} finding that the arms contribute 70.3% of propulsion for male swimmers, the use of fins can significantly reduce the shoulder load. PK initially began swimming a total of 800 meters/practice every other day with 75% of the distance swum with fins. Swimming volume was advanced approximately 10% per week. Once PK was able to perform 1200 meters of freestyle with use of fins and taping, he was instructed to perform 50% of his swimming volume without fins. Over the next 6 weeks, use of fins was gradually reduced and the swimming distance was increased until PK was able to swim a full practice without fins.

CONCLUSION

Shoulder pain is common among swimmers and can be attributed to a variety of risk factors including training errors and physical impairments. In-pool return to swim protocols have been described previously for swimmers who have been deactivated from swimming due to injury and/or who have full rotator cuff and periscapular muscle strength. However, clinicians are often left without clear guidance for treating swimmers with shoulder pain and physical impairments who continue in-pool practice. The authors have found the combination of dryland and in water training modifications as well as the use of NMES and taping to supplement a strengthening and stretching program has facilitated return of competitive swimmers to pre-injury levels. However, there are limitations to the protocol presented and the authors cannot conclude that this program is more effective than a traditional physical therapy program would be without the addition of NMES, taping, and training modifications. Therefore, further research is needed and welcomed to compare the efficacy of this and other protocols to determine optimal methods for managing shoulder pain in competitive swimmers.

CONFLICTS OF INTEREST

None

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Table 2

Table 3
Injury prevention strategies in team settings should not overlook early detection and secondary prevention. Monitoring systems may be an effective approach to detect common and troublesome injuries, such as hip and groin pain in football (soccer) players. The purpose of this International Perspective is to share our experiences with monitoring hip and groin pain in youth academy football and discuss challenges that surfaced. We consider why players may not accurately report pain, their perceptions of groin pain, and whether all groin pain is clinically meaningful.

Level of Evidence

Sports medicine staffs working in teams settings should emphasize injury risk reduction. Primary prevention strategies such as FIFA 11+, Nordic hamstring exercise, and Copenhagen adductor exercise programs are successful for hip and groin pain.\(^1,\) Secondary prevention has been suggested using monitoring systems in Australia and Scandinavia. This approach to early detection can combat troublesome hip and groin pain in athletes,\(^3-5\) but it is not without challenges.

Hip and groin pain are common in elite male football (soccer) players,\(^6,\) and recent authors have also shown high rates in youth players.\(^3,\) In a retrospective anonymous survey after pre- and early season,\(^9\) we observed 77% of US academy football players had experienced groin pain of varying intensities (Figure 1). We had simultaneously implemented a weekly monitoring system to screen groin pain in the academy. Surprisingly, the retrospective survey results did not align with weekly check-ins, where only 58% of players reported pain. We began to question if players were under-reporting their hip and groin symptoms to our medical personnel (physical therapists, athletic trainers, team doctors) at weekly check-ins. The purpose of this International Perspective is to share our experiences with monitoring hip and groin pain in youth academy football and discuss challenges that surfaced. This may have implications for worldwide adoption of secondary prevention strategies in elite youth football.

One challenge for monitoring systems is relying on players themselves to accurately report their symptoms. Not only did we identify that groin pain was under-reported during weekly check-ins compared to retrospective reports (58% at weekly check-ins versus 77% at the 12-week retrospective survey), but we also retrospectively asked players why some might under-report pain. Players’ perceptions of the monitoring system were gauged by asking if any of the following reasons might lead to under-reporting: 1) fear that reporting pain would restrict participation, 2) believing groin pain is normal, 3) not wanting to report in front of teammates, 4) reporting pain would make others question

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*Corresponding Author: Matthew D. DeLang Right To Dream Academy Old Akrade, Eastern Region, Ghana +233 020 111 6199 mdde-lang@gmail.com*
that player’s toughness, or 5) a free-text option. A staggering 41% of academy players feared that reporting pain would lead to medical personnel preventing them from training/playing. In hindsight, we see that temporarily sidelining players for a thorough clinical examination backfired in relation to the trust between medical personnel and players. This rationale for players’ under-reporting makes sense: if they perceive reporting symptoms as a threat to their participation, they will be less likely to report pain. The lesson is learned – medical personnel must consistently build trust with players and provide additional education to enhance player adherence to a monitoring system.

Another interesting lesson was how football players perceive groin pain. The survey revealed that 26% of players believed hip and groin pain was normal. Additionally, these statements appeared via free-text response: "my discomfort hasn’t affected me", "it didn’t hurt that bad", and "pain wasn’t bad enough to report". Quite a few players did not find groin pain to be particularly concerning. This provided an opportunity to better understand our athletes. Players may perceive groin pain as a normal byproduct of football participation, and medical personnel must decide which pain is concerning and which is not. Transparent education and communication between all stakeholders (medical, coaches, players) may help understand the intention of the monitoring system: to collect information, detect problems, and intervene appropriately with secondary prevention and treatment.

Upon establishing consistent and accurate reporting with the athletes, a monitoring system provides the means to implement secondary injury prevention. Ideally, medical personnel would intervene when groin pain is meaningful (i.e., at-risk for worsening severity, time-loss, and high injury burden), while also supporting participation when it isn’t (i.e., normal soreness and fatigue). Herein lies another big challenge: what are ways to differentiate between meaningful and meaningless groin pain? The Doha Agreement clinical taxonomy provides a standardized framework to classify groin pain. Perhaps monitoring pain using this taxonomy, coupled with symptom duration and intensity, can help medical personnel pinpoint when pain that spreads to another location, persists over time, or reaches higher intensity becomes more concerning.

The authors of this perspective have identified challenges encountered during hip and groin monitoring, including why athletes might under-report pain, whether all groin pain is meaningful, and knowing how and when to intervene. Researchers implementing monitoring systems should be encouraged to share experiences to add to the global perspectives of monitoring athletes for early detection. We believe improving communication between all stakeholders promotes shared decision-making for safe participation and optimal performance, and that trust is essential so that players and medical personnel can profit from the monitoring system. Learning how and when to intervene will improve injury risk reduction strategies in team sports settings. Presently, this may not be as simple as it sounds, as further development around such strategies and their implementation may be needed before athletes view close monitoring as a “friend”.

COMPETING INTERESTS

None.

PATIENT CONSENT FOR PUBLICATION

The survey referred to in this paper was approved by the University of Texas Southwestern Institutional Review Board and all academy players completed informed consent and assent. Those under the age of 18 were signed by a parent or guardian.

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DO WEIGHTED BASEBALLS ENHANCE VELOCITY?

The general consensus to this question will likely be that, yes, weighted balls enhance velocity. But this deserves more attention.

In our 6-week prospective study, we showed that a group of high school athletes using weighted balls had a significantly greater improvement of 3.3% in pitching velocity compared to a control group.6

But when analyzing the data, we showed that not everyone increases velocity and that many people in the control group also improved. Eighty percent of people in the weighted ball group enhanced velocity, with 8% showing no change, and 12% showing a decrease in velocity. Furthermore, 67% of people in the control group also improved their velocity, with 19% showing no change, and 14 showing an actual decrease.

A similar 6-week study by Marsh et al.7 reported no significant change in velocity in collegiate and professional pitchers after a 6-week program. A recent meta-analysis by Caldwell et al.8 also noted several studies that concluded with no significant change in velocity.

Thus, it appears that while weighted balls may help some enhance their velocity, not everyone will see improvement and some will even see a decline. This may have a lot to do with the wide variety of definitions of a "weighted ball" training program. Variations in the weights of the ball, the amount of throwing, and the drills performed can all impact results. Going forward, future research should attempt to delineate the variables associated with performance enhancement and to determine if a specific population may find more benefit than others.

THE BIOMECHANICS OF WEIGHTED BASEBALLS

Very little information is known about the biomechanics of weighted balls. Fleisig et al.9 showed no significant kinematic changes when throwing balls weighing between 4-7oz, but did note a significant increase in peak varus torque at the elbow with underload balls, and a general increase in elbow torque across all ball weights when comparing weighted ball drills and pitching off a mound. Okoroha et al.10 showed a significant increase in varus torque that increased as the weight of the ball increased from 3-6 oz in youth.

While those studies are helpful, they only look at a small piece of weighted ball training. It’s very common for athletes to include throws from various positions with balls weighing from 2oz to 2lbs and more.

But more importantly, peak torque may not be the only relevant metric to observe. The total amount of torque over the course of the throw and the contribution of muscular fatigue should not be overlooked. Both could theoretically stress both the static and dynamic stabilizers of the shoulder and elbow.
Future research should continue to look at the biomechanics as programs evolve.

**THE MECHANISM OF VELOCITY ENHANCEMENT**

As we continue to study weighted ball programs, there is still some uncertainty as to why they may help enhance velocity. However, recent research from our group has shed some light on this that may explain both the mechanism of efficacy, as well as the potential injury risk.

Subjects in our 6-week program study showed a significant increase in shoulder external rotation of 5 degrees at the conclusion of the study, which did not occur in the control group. This finding surprised us and led to our next study on the acute effects of weighted ball throwing on shoulder range of motion (ROM).\(^\text{11}\)

In this study, we showed that subjects that threw overload weighted balls had a significant increase in shoulder ROM that increased as the weight of the ball increased. Throwing 16-32oz balls for a total of 27 throws at largely submaximal intensities resulted in an 8-degree increase in passive shoulder external rotation. It should be noted that in a past study of ours, we showed that professional pitchers that threw a 45 pitch session off the mound at full intensity did not show a change in external rotation ROM.\(^\text{12}\)

Past studies have shown that pitching velocity is correlated to shoulder external rotation, however, this also correlated to increased stress.\(^\text{13–16}\) Based on these studies, it appears that the gain in external rotation ROM from throwing weighted balls is likely the contributing factor to velocity improvements.

**THE SAFETY OF WEIGHTED BALL PROGRAMS**

While performance enhancement is important for athletes, doing so in a way that does not significantly increase injury risk is also important. In our prospective study on weighted ball training, we showed that almost 25% of subjects sustained an injury to their shoulder or elbow. Most injuries occurred in the subsequent baseball season, not during the program. To date, this is the only study to follow players after a program. This matches our anecdotal experience and of others.

Based on what we have learned, this seems to make sense. We know that throwing weighted balls is an added stress to the joints. We know that they increase shoulder external rotation. We know that this can enhance velocity, but also increase stress on the arm.

**THE FUTURE OF WEIGHTED BALL TRAINING**

While we have learned so much over the last several years, there is still much more to learn. Future research should continue to explore the safest and most effective use of weighted balls for training.

It all comes down to physics. Weighted balls aren’t evil and aren’t the cause of injuries. They just change the stress. They also aren’t magical and don’t work to enhance velocity with everyone. If we are going to try to find ways to enhance performance without sustaining injuries, we need to understand this simple fact and build programs based on science.

We are also overdosing some of our athletes if we don’t plan these programs appropriately. Taking a break from throwing off a mound is important to reduce overuse injuries. Olsen et al. previously showed that pitching less than 8 months out of the year can reduce injuries by 500%.\(^\text{17}\) The previous thought process in the baseball community was that these weighted ball programs can be used without consequence. However, it appears that weighted balls are equal to or more stressful than throwing off a mound.

**RECOMMENDATIONS**

Based on our current understanding of the science, we recommend the following:

- Moving away from generic programs used by a variety of athletes, or entire groups of pitching staff, towards a more individualized program is imperative.
- Strict inclusion and exclusion criteria need to be established prior to initiating a program.
- Programs with extreme weights or volume should be avoided in the skeletally immature athlete until a proper physical base is established.
- Programs should be scaled based on the level and experience of the player.
- Different programs should be designed based on the time of the year and specific goals of the athlete.
- Workloads should be monitored to assure weighted balls are included in throw counts and overall program design.
- Monitoring the athlete must be included to assure they are handling the added stresses that are involved.

In summary, when the activity being performed approaches the limits of soft tissue integrity, we need to assure we are dosing the program accordingly. More is not better. If we’re going to utilize a program that pushes our physiological limits, then we need to be much more careful, follow the science, and be specific with the application.

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