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Background: Adolescent athletes are experiencing an increased number of concussions. There is currently a debate within the medical community regarding the most effective and safe treatment approach for this population, post-concussion. Interventions currently range from cognitive and physical rest to various types of physical activity, including aerobic exercise. While there are systematic reviews that focus on rest as the main intervention, there are no other systematic reviews that focus on the effects of aerobic exercise on concussion recovery in adolescent athletes.

Purpose: The aim of this systematic review and meta-analysis was to investigate the effectiveness of aerobic exercise on concussion recovery for adolescent athletes compared to an alternate intervention.

Study Design: Systematic Review and Meta-Analysis

Methods: A computer-based search (population: adolescent athletes with concussions, intervention: aerobic exercise, comparator: non-aerobic interventions, outcome: symptom severity and recovery time) was performed. Databases including PubMed, CINAHL, SPORTdiscus, ProQuest, and Scopus were searched up to December 2019 for randomized controlled trials published since 1965. A hand search of relevant articles and exploration of grey literature was also completed. Data were extracted for the following information: interventions prescribed, outcome measures, and overall results of the study. A meta-analysis was performed for aerobic interventions using standardized mean difference as the summary measure of effect.

Results: Five studies, which all held a moderate to low risk of bias according to the PEDro scale, met the inclusion criteria for this systematic review and meta-analysis. Overall results favored aerobic exercise for both acute and prolonged recovery symptoms as demonstrated by a decrease in symptom severity and improved recovery time. The meta-analysis revealed a moderate effect size in favor of the intervention group (SMD: 0.51, CI: 0.02, 0.81, p=0.00) when looking at the three outcome measures combined: Post-Concussion Symptom Scale, Post-Concussion Symptom Inventory, and recovery time.

Conclusion: The results of this systematic review and meta-analysis indicate that there is currently moderately significant evidence in support of implementing an aerobic exercise program for adolescent athletes with both acute and prolonged recovery concussion symptoms. Additional higher quality studies are needed to continue to study the effectiveness of aerobic exercise in post-concussion treatment of adolescents.

Level of Evidence: 1a

Keywords: adolescents, aerobic exercise, athletes, concussion, movement system

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INTRODUCTION
A concussion or mild traumatic brain injury (mTBI) is a chemical change that occurs in the brain due to a direct blow to the head or a hit to the body that causes the head and brain to move rapidly back and forth.1 Signs and symptoms often appear soon after the injury and may include confusion, personality changes, brief loss of consciousness, dizziness, nausea, vomiting, light or noise sensitivity, headache, and feeling foggy.1 A common population afflicted by concussions are adolescent athletes. According to the Centers for Disease Control and Prevention (CDC), nearly 330,000 children, ages 19 and younger, were treated in emergency departments for sport and recreation-related concussions and traumatic brain injuries in 2012. The rate of emergency department visits for sport-related concussions more than doubled in the adolescent athlete population between 2001-2012.2 Current standard treatments for concussion include both physical and cognitive rest, as well as gradual progression to participation in activities.3 However, the activities and their dosage remain a debate within the medical community. While there are multiple guidelines regarding adult athletes and concussion recovery, there is a lack of standardization regarding interventions within the adolescent athlete post-concussive population. Physical activity, including aerobic exercise, is beginning to be explored as a standard intervention. Aerobic exercise has been shown to such as decreasing risk for Type II diabetes, cancer, hypertension, obesity, depression, and osteoporosis.4 Therefore, aerobic exercise should be explored for brain health, including its effects on concussion recovery. Despite preventative measures being taken, concussions still occur. Therefore, it is imperative to explore evidenced-based interventions for post-concussive rehabilitation. Previous systematic reviews (SRs) have primarily focused on rest and cognitive testing as the main interventions to promote concussion recovery.5 However, there is evidence that suggests active treatment strategies are favorable in the process of concussive recovery for athletes.5 The adolescent athlete may be the most vulnerable to long-term consequences of concussions.6 Exploring active recovery as a strategy as for reducing post-concussive symptoms and accelerating return to sport-specific activities is warranted. As a result, the purpose of this systematic review (SR) and meta-analysis (MA) was to investigate the effectiveness of aerobic exercise on concussion recovery for adolescent athletes compared to an alternate intervention.

METHODS
Protocol and Registration
The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) was utilized to guide this review. The PRISMA checklist is a 27-item list designed to improve reporting for authors of both systematic reviews and meta-analyses.7 Research topic, pilot title, and protocol were registered online on the PROSPERO International Prospective Register of Systematic Reviews database with registration number: CRD42019121764. PROSPERO provides an extensive list of registered systematic reviews to attempt to prevent duplication and reduce reporting bias.

Eligibility Criteria
Eligibility for this review included randomized controlled trials (RCTs) that compared aerobic exercise to alternate interventions (i.e. stretching, manual therapy, vestibular training, rest) for adolescent athletes with a clinically diagnosed concussion. Studies that compared aerobic exercise to control groups were also included. Included articles were limited to RCTs in an attempt to improve the quality of the data analyzed. Aerobic exercise was defined as activities that elevated heart rate above resting heart rate or increased Rate of Perceived Exertion (RPE) to a moderate level or higher. Concussion was defined using the Centers for Disease Control and Prevention statement, which classifies it as a type of traumatic brain injury caused by a blow to the head or a hit to the body, causing the head and brain to move rapidly back and forth.2 Studies published prior to 1965 were excluded since the MESH term “brain concussion” was first introduced in 1965. Non-English studies were excluded as well as studies that investigated the effectiveness of a one-time intervention.

Search Strategy, Databases Utilized, and Study Selection
The following databases were searched: PubMed, CINAHL, ProQuest, Scopus, and SPORTdiscus.
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The search strategy included three main classifications: concussions, adolescent athletes, and aerobic exercise. Synonymous terms were defined and used with the main classification terms to mark the search. Similar terms were used in each database while using database-specific terms, such as Medical Subject Heading (MESH) terms when relevant. An example of a specific search strategy can be found in Appendix 1. A hand search of relevant articles and inspection of grey literature, including clinicaltrials.gov and opengrey.eu, were also done for any studies that were not identified in the database search. The initial search was conducted in January 2019, and the final search was performed in December 2019.

Titles, abstracts, and full texts of studies retrieved using the search strategy were screened independently by two authors to identify studies that potentially met the inclusion criteria or belonged within the exclusion criteria. Any disagreement between the two authors over the eligibility of particular studies that could not be resolved by consensus was resolved with a third reviewer's vote. A Cohen's unweighted Kappa was calculated for agreement during both title and abstract selection and full-text selection. A Kappa of less than or equal to 0 is considered no agreement; 0.01 to 0.2, none to slight agreement; 0.21 to 0.40, fair; 0.41 to 0.60, moderate; 0.61 to 0.8, substantial; and more than 0.8, almost perfect agreement.8

Data Extraction and Analysis

Data from the final full text articles were extracted by two authors, which were then cross checked and agreed upon. Data extracted included sample size, mean age of participants, and interventions. Outcome data extracted from the articles included the following outcome measures: The Post-Concussion Symptom Scale (PCSS), the Post-Concussion Symptom Inventory (PCSI), and recovery time.

The PCSS is a 21-item patient-rated scale. Symptom severity is rated using a 7-point Likert scale with 0 meaning “no symptom” and 6 meaning “severe”. Moderate test-retest reliability has been reported with an intra-class correlation coefficient (ICC) of 0.62.9,10 The PCSI is a self-report form that focuses on symptoms in the cognitive, emotional, sleep, and physical domains. For individuals between the ages of 5-7, there are 13 items to rank. For individuals ages 8-12, there are 25 items to rank. For individuals ages 13-18, there are 26 items to rank.11 Moderate to high interrater reliability has been reported for the child report (two separate reports that assess ages 5 to 7 and 8 to 12), as well as moderate to strong test-retest reliability (ICC = 0.65-0.89).11 However, it is reported that the strongest data for adolescents with concussions supports using the PCSS over the PCSI.9 Recovery time is defined as being the number of days to recovery since the date of injury.12 Recovery is defined as symptom resolution to normal, confirmed by a normal physical examination.12

Means and standard deviations for aerobic exercise and alternate interventions were also synthesized in each study. Meta-analyses were made using Comprehensive Meta-Analysis Version 3 where applicable. All meta-analyses were done using standardized mean difference (SMD) as the summary measure of effect. SMD with 95% confidence intervals (CI) were used. I² statistics were calculated in order to determine the level of heterogeneity between included studies. The I² statistic is more useful than the Q test, which only indicates the presence versus absence of heterogeneity.13 Percentages used by Higgins and Thompson14 were utilized to quantify the magnitude of heterogeneity: 25% = low, 50% = medium, 75% = high heterogeneity. Utilizing the scale, if I² was <50%, a fixed effects model was used, and if the I² was >50%, a random effects model was used. The I² value for this meta-analysis was 61.34%, therefore, a random effects model was used. Interpretation of effect size used Cohen’s criteria for pooled estimates.15 An SMD of 0.2-0.4 = small effect; 0.5-0.7 = moderate effect; 0.8 and higher = large effect.16

Quality Assessment

Two authors independently assessed the risk of bias in all included studies using the PEDro Scale. Disagreements in the quality of the studies were discussed between the two authors. If a consensus was not determined, a third author made the ultimate decision. The PEDro Scale is a criteria-based scale used to assess the quality of randomized controlled trials. There are 11 criteria used in this scale regarding topics such as eligibility criteria, randomization, blinding, and statistical reporting.17 A higher score represents a higher quality study.17
RESULTS

Study Selection

The results of the initial search produced 2,442 titles. After duplicates were removed, 2,175 titles were found. Titles and abstracts were then screened by two authors, and 2,133 articles were excluded. Hand search and grey literature searches were then completed and no additional randomized control trials were found. After title and abstract assessment, 42 articles were deemed appropriate for full-text review, with an observed $\kappa = 0.46$, confidence interval (CI) = 0.30 - 0.62, indicating moderate agreement. Non-randomized control trials were excluded resulting in five articles being included in the systematic review and meta-analysis as they satisfied the inclusion criteria. After screening the accepted full text articles, the observed $\kappa = 0.90$, CI = 0.69 - 1, exhibiting almost perfect agreement. After deciding on the full text articles to include $\kappa = 1$, CI = 1 - 1, demonstrating perfect agreement. There was no need to call on a third author for a tie-breaker decision. Details of the study selection process can be found in Figure 1.

Study Characteristics

Cycling was used as the aerobic intervention for three out of the five included studies while the remaining two used treadmill training. Rest was used as a part of usual care for the control groups in two out of the five included studies. Patient education and medication was used along with rest for one of those two usual care control groups. Stretching was used for the control groups in three of the five included studies. The intervention and control groups were matched by age in all studies. In total, 179 subjects were used as participants; 98 were males, and 82 were females. Acute symptoms versus prolonged recovery were defined by either less than 4 weeks (acute) or greater than four weeks (prolonged recovery). Other pertinent study characteristics can be found in Table 1.

Quality Assessment

Two reviewers assessed the risk of bias of the five articles included using the PEDro scale. Each article received a PEDro Scale score (see Table 2). An unweighted kappa was calculated to evaluate the level of agreement between the two authors ($\kappa = 0.82$, CI = 0.66 - 0.99, which is almost perfect agreement). None of the articles met Criterion 5 or Criterion 6 due to an inability to blind participants and researchers to specific interventions. All of the articles met Criterion 9 and Criterion 10 because outcomes were reported on at least one of the groups in all articles. Thus, the included articles were of good quality with regard to bias as they all scored 6 or 7 out of 10 items (Criterion 1 was excluded). These articles were deemed acceptable by all group members for use in this study.

Outcomes

PCSS

Two of the five studies$^{19,20}$ used in the systematic review evaluated symptom severity using the PCSS (see Table 3, Figure 2). However, only one of the studies that used the PCSS, Chan et al.$^{19}$ was included in the meta-analysis as Micay et al.$^{20}$ reported results as a total point value of change for symptom severity rather than providing baseline and final measurement scores. Results demonstrated a decrease in symptom severity in prolonged recovery symptoms with aerobic exercise with a moderate effect size (SMD: 0.622, CI: -0.30, 1.54, p = 0.19).
Two of the five studies\textsuperscript{21,22} used in the systematic review and meta-analysis evaluated symptom severity using the PCSI (see Table 3, Figure 3). Results demonstrated a decrease in symptom severity with aerobic exercise with a moderate effect size (SMD: 0.75, CI: 0.13, 1.37, \(p=0.02\)). Both studies analyzed prolonged recovery symptoms.

**Recovery Time**

Two of the five studies\textsuperscript{12,20} used in the systematic review and meta-analysis evaluated recovery time (in days) (see Table 3, Figure 4). Leddy et al\textsuperscript{12} evaluated recovery time by the number of days from the time of injury to the third consecutive day in which the individual's PCSS score fell below 7. Micay et al\textsuperscript{20} determined recovery time by reviewing each participant's electronic medical record for their return to play status (measured by days). Both studies evaluated acute symptoms. Results demonstrated a decrease in recovery time with aerobic exercise with a small effect size (SMD: 0.20, CI: -0.64, 1.05, \(p=0.64\)).

**Overall**

When looking at three outcome measures combined, PCSS, PCSI, and recovery time, there is a moderate
Table 3. Outcomes. PCSS = post-concussion symptom scale, PCSI = post-concussion symptom inventory, SD = standard deviation.

*The PCSS data for the Micay et al study is reported as a total point value of change for symptom severity rather than baseline and final measurement scores.

<table>
<thead>
<tr>
<th>Study Name</th>
<th>Outcome</th>
<th>Time Point</th>
<th>Effect Size (Standardized Mean Difference)</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain, 2017</td>
<td>PCSS</td>
<td>Baseline</td>
<td>Intervention Mean Baseline Outcome Measure (SD)</td>
<td>-0.62 (0.30 - 1.54)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Final</td>
<td>Intervention Mean Final Outcome Measure (SD)</td>
<td></td>
</tr>
<tr>
<td>Micay*</td>
<td></td>
<td></td>
<td>Control Mean Baseline Outcome Measure (SD)</td>
<td>1.58 (0.42 - 2.74)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control Mean Final Outcome Measure (SD)</td>
<td></td>
</tr>
<tr>
<td>Kurowski, 2017</td>
<td>PCSI</td>
<td>Baseline</td>
<td>Intervention Mean Baseline Outcome Measure (SD)</td>
<td>0.76 (0.05 - 1.57)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Final</td>
<td>Intervention Mean Final Outcome Measure (SD)</td>
<td></td>
</tr>
<tr>
<td>Yuan, 2017</td>
<td></td>
<td></td>
<td>Control Mean Baseline Outcome Measure (SD)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control Mean Final Outcome Measure (SD)</td>
<td></td>
</tr>
<tr>
<td>Leddy</td>
<td></td>
<td></td>
<td>Recovery Time (Days)</td>
<td>0.01 (p-value)</td>
</tr>
<tr>
<td>Micay</td>
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</table>

Figure 2. Standardized difference in means in individual studies for PCSS.

Squares represent study-specific findings, and diamond represents summary estimates of fixed/random effects meta-analysis.

PCSS = post-concussion symptom scale, Std diff in means = standardized difference in means, CI = confidence interval.

Figure 3. Standardized difference in means in individual studies for PCSI.

Squares represent study-specific findings, and diamond represents summary estimates of fixed/random effects meta-analysis.

PCSI = post-concussion symptom inventory, Std diff in means = standardized difference in means, CI = confidence interval.

Figure 4. Standardized difference in means in individual studies for recovery time.

Squares represent study-specific findings, and diamond represents summary estimates of fixed/random effects meta-analysis.

Std diff in means = standardized difference in means, CI = confidence interval.

Figure 5. Standardized difference in means in individual studies for overall outcomes.

Squares represent study-specific findings, and diamond represents summary estimates of fixed/random effects meta-analysis.

PCSS = post-concussion symptom scale, PCSI = post-concussion symptom inventory, Std diff in means = standardized difference in means, CI = confidence interval.
effect size in favor of the aerobic exercise intervention group (SMD: 0.51, CI: 0.02, 0.81, p = 0.00) (see Table 3, Figure 5).

DISCUSSION
The majority of the studies reported significant post-concussion improvements with aerobic exercise, suggesting that aerobic exercise may be beneficial for concussion recovery in adolescent athletes.

There were limitations with the included studies that have the potential to affect the overall conclusion of this review. Neither the participants nor researchers were blinded to the interventions being completed in the included studies for this SR/MA. This may have created a “placebo” effect, meaning that reductions in the patient’s symptoms could have occurred due to the participants knowing which intervention they were receiving and having a positive outlook on the effects of that intervention. The studies selected targeted the population of concussed adolescent athletes, which produced a limited number of RCTs. Finally, while the sample sizes within the studies were small; the meta-analysis was completed on a sample of 90.

There was variability in the intervention that the control groups received in the individual studies. This makes between study comparisons less precise and more challenging to develop an understanding of the true influence of interventions. Finally, there was variability in reporting results. The majority of articles reported their data as baseline and final measurement scores. However, one study reported PCSS results as a total point value of change for symptom severity. This discrepancy in reporting resulted in the exclusion of this study’s PCSS findings from the MA. If all studies uniformly reported results, then more studies could be compared objectively, which would strengthen the conclusions drawn from this data.

There were several strengths to the way in which the SR was conducted. First, the PRISMA guidelines were incorporated in the reporting of the findings to ensure transparency. Secondly, only RCTs were included. An RCT is an optimal research design to minimize bias and is well suited to answer research questions pertaining to the effect an intervention has on a population. Finally, the review process proved to be reliable. This ensured that the appropriate studies were included in this SR/MA.

While the Pedro scale is widely used for quality assessment, there are not published cut-off scores to classify a study as high, moderate or low quality. In the absence of this cut-off scored, the guideline was followed of a higher score indicating a higher quality study. This could be construed as a weakness.

While other systematic reviews have studied the effect of aerobic exercise on concussion, none have focused on an adolescent population. An SR published in 2017, which did not explore a specific age group, suggests that after a brief (24-48 hour) period of physical and cognitive rest, patients should be encouraged to gradually increase activity. In addition, the abovementioned SR also supports the use of cervical and vestibular rehab as indicated. Another SR/MA without an age-specific population of interest had similar findings that physical exercise (which included stretching as well as aerobic activity) improves symptoms in patients with concussion.

One possible explanation for the significant results found in the current SR/MA is related to the physiology of the brain. Aerobic exercise may positively affect various aspects of brain healing, including improvement in cerebral blood flow, blood oxygen extraction, autonomic control pathway, and neuroplasticity. All of these may encourage structural reorganization of the brain that can positively impact tissue healing.

A second prospective explanation for the post-concussive improvement seen in adolescents treated with aerobic exercise deals with the biopsychosocial model, which is a clinical model that suggests that pathological experiences are affected by multiple variables. One component of the model focuses on the relationship between mental and physical health, suggesting that subjective experiences are not confined to physiology. It may be that once adolescents are given permission to participate in physical activity after an injury, negative illness beliefs, such as fear avoidance behaviors, are countered. Adolescents can then reintegrate into their social and recreational activities, which can lead to both physical and mental health benefits.
Implications for Further Research

Future research should focus on return to play or return to learn protocols to guide practice for efficient and safe returns. This could include time until symptoms subside, time until the athlete is medically cleared, and which interventions provided the fastest and safest return. These items should be researched using a randomized controlled trial design comparing an aerobic exercise experimental group to a resting or stretching control group. Future research needs to be completed on adolescent athletes directly after experiencing concussion symptoms. This could be within the first few days following diagnosis of the concussion. Randomized controlled trials are limited in this area as not many studies choose to target athletes in the acute phase after developing concussion-like symptoms.

CONCLUSION

The results of this systematic review and meta-analysis indicate that there is currently moderately significant evidence in support of implementing an aerobic exercise program for adolescent athletes with both acute and prolonged recovery concussion symptoms. Additional higher quality studies are needed to continue to study the effectiveness of aerobic exercise in post-concussion treatment of adolescents.

REFERENCES


### Appendix 1. Search Strategy

<table>
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ABSTRACT

**Background:** Reviews on superior labral anterior to posterior (SLAP) injuries have been reported in the literature. However, current reviews have not focused on the success of athletes return to their previous level of sport or athletic performance.

**Hypothesis/Purpose:** Systematically review return to sport (RTS) and return to sport at previous level (RTSP) proportions after SLAP injury while reporting any additional performance metrics and outcome measures.

**Study Design:** Systematic Review & Meta-Analysis.

**Methods:** A computer assisted literature search of MEDLINE, CINAHL, Embase and SportDiscus databases utilizing keywords related to RTS post-surgery for SLAP tear was implemented. The **Preferred Reporting Items for Systematic Reviews and Meta-Analyses** guidelines were utilized for study methodology. Quality assessment utilized the MINORS scale.

**Results:** Twenty-two studies (617 athletes) qualified for analysis. Based on limited evidence from level 3b to 4 studies, athletes RTS post intervention for SLAP injury occurred at a rate of 93% (95% CI:87 to 98%) and overall RTSP rate was 72% (95% CI:60 to 83%). The mean time to RTS post intervention was reported in 59% of studies at 6.9±2.9 months. Patient reported outcome measures (PROM's) were reported in 86% of studies. There was limited reporting of performance statistics, rehabilitation guidelines, return to sport criteria, and information regarding SLAP diagnosis in the available studies. None of the included studies reported post-surgical athletic performance or career longevity.

**Conclusions:** Limited evidence suggests that less than three in four athletes return to their previous level of sport participation after SLAP injury intervention. Treatment success for an athlete with SLAP injury remains relatively unknown as only 59% of included studies clearly delineate RTS from RTSP and neither athletic performance nor career longevity were reported in any included studies. Future studies of higher quality are required for this determination.

**Level of Evidence:** Level 1a

**Keywords:** Labrum, movement system, pitching, return to play, return to sport, shoulder, SLAP tear
INTRODUCTION
Superior labrum anterior to posterior (SLAP) injury was first described by Andrews et al.1 in 1985 with further classification in 1990 by Snyder et al.2 Repetitive overhead throwing is a primary mechanism for SLAP injury,3 along with acute mechanisms such as direct contact with the ground.4 Despite the long history of the condition, SLAP injuries remain a prevalent problem in both overhead throwing athletes4 as well as contact athletes.4

Original reporting on surgical intervention for SLAP injuries suggested low patient satisfaction in throwing athletes, although a systematic review on return to sport (RTS) suggests high levels of satisfaction in athletes, but possibly not overhead throwing athletes, following repair of SLAP type II injury.5 This review, published in 2012, did not assess pre- to post-surgery significance of change in patient-reported outcome measures or satisfaction and did not assess study quality.5 Additionally, clear distinction in RTS versus return to sport at a previous level (RTSP) is required to accurately determine the success of any intervention. This has been well outlined in other injuries such as ulnar collateral ligament reconstruction,6 and anterior cruciate ligament reconstruction.7

Therefore, the purpose was to systematically review return to sport (RTS) and return to sport at previous level (RTSP) proportions after SLAP injury while reporting any additional performance metrics and outcome measures. The intent was to discriminate RTS from RTSP while reporting any additional performance metrics with the hypothesis that the literature would demonstrate a high level of RTS, especially among more recent literature.

METHODS
Protocol and Registration
The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to evaluate and assess study methodology.8 This review was prospectively registered with Prospero (CRD42018087973) after completion of preliminary search and initiation of formal screening on February 2, 2018.

Identification and Selection of the Literature
A medical librarian assisted computerized search was conducted in MEDLINE, CINAHL, Embase and SportDiscus from each database inception to May 18, 2018. Medical Subject Headings (MeSH) terms and selected free-text terms were utilized for “SLAP tear,” “Surgery,” “return to sport,” “baseball,” “performance,” “clinical trials,” “cohort studies,” and “literature review” (Appendix 1). Reference lists for all selected publications were also hand searched for missing publications. Citations were tracked in EndNote (version X7, Thomson Reuters).

Selection Criteria
As computerized search results for diagnostic accuracy data frequently omit relevant studies,9 systematic reviews and included studies were also screened to detect eligible studies that were not identified by the electronic search. To be included in the systematic review, the studies had to satisfy the following criteria:

- **Study design:** Randomized control trials, prospective and retrospective intervention or observational studies with a population greater than 10 athletes investigating return to sport (and, if present, surgical treatment versus conservative treatment) for shoulder labral injury or conservative treatment. Systematic reviews, conference abstracts, case studies, narrative reviews and non-peer-reviewed studies were excluded. Only studies written in the English language were included.

- **Participants:** Athletes (as defined by each respective study) in any age group or athletic competition level (professional, college, high school or middle school, amateur/recreational) with diagnosis of SLAP tear (as per report from each respective study). Non-athletes were defined as those who did not participate in sport. If the studies did not define the population of interest, but stated the patients returned to sport, we assumed they were athletes. Athletes with concomitant surgical procedures (e.g. rotator cuff tear, Hill-Sach’s lesion) performed in combination with SLAP surgical/non-surgical procedures were included provided at least 80% of participants in a study were treated primarily for SLAP tear.10-13

- **Intervention:** At least 80% of the athletes had to be treated with surgical/non-surgical intervention for SLAP tear. Studies where intervention focused primarily on other procedures (e.g. Bankart tear, rotator cuff tear) were excluded.
• **Comparator:** When available, non-surgical treatment or no treatment. When available, other surgical treatment types (e.g. open versus arthroscopy)

• **Outcomes:** Proportion of athlete RTS (any level) and RTSP (return to sport at the preinjury level of competition). Secondary outcomes included patient-reported outcome measures, surgical complication and failure rates, time to RTS and RTSP, athlete and sport types included, surgical procedure(s), post-surgical athletic performance, career longevity, or return to sport criteria. Also if possible, we will make distinction between proportion of athlete RTS based on varying levels of athletic participation (e.g. high school, college, professional).

• **Time:** All post-surgical time frames reporting either RTS or RTSP were included. There were no limits to year of study publication.

To identify relevant studies, two reviewers independently screened titles and abstracts of all identified citations. Full-text studies were retrieved and screened independently by the two reviewers if the abstract provided insufficient information to establish eligibility, or if the study passed the first eligibility screening. Disagreements were resolved by consensus. A third reviewer was utilized when consensus regarding study inclusion/exclusion could not be reached. The interrater reliability for the title \( \kappa = 0.54 \) (95% CI: 0.42 to 0.66), abstract \( \kappa = 0.63 \) (95% CI: 0.51 to 0.75), and full text \( \kappa = 0.76 \) (95% CI: 0.66 to 0.87), suggest moderate and substantial levels of agreement respectively.

**Quality Assessment**

Two reviewers independently assessed the risk of bias for each included study using the Methodological Index for Non-Randomized Studies (MINORS) scale. This tool was specifically developed and validated to evaluate the quality of nonrandomized surgical studies. It includes eight items for non-comparative studies and an additional four items for comparative studies. Each item is scored on a 0-2 scale with a total score of 16 available for non-comparative studies and 24 for comparative studies. Studies that met >75% of criteria were considered High Quality, 50-74% considered Moderate Quality, 25-49% considered Low Quality, and <25% considered Very Low Quality. Studies were not excluded from the analysis based on the assessment of risk of bias and disagreements were resolved via consensus. Definitions for levels of evidence for pooled results were guided by previous recommendations.

**Data Extraction**

Data were extracted into a customized database by two authors and confirmed by a third author. Disagreements were discussed between the two authors, with a third author utilized to settle any discrepancies. Data elements included sample size, athlete population characteristics, quality elements, return to sport criteria, return to sport proportion, time to return to competition, athletes’ demographic characteristics (e.g. age, gender, sport, competition level), level of evidence, and secondary outcome measures (performance statistics).

**Definition of Return to Sport and Return to Sport at Previous Level**

Previous definitions of return to sport and return to performance are unable to both objectively determine surgical treatment success and actual sport performance. Therefore, it was chosen to operationally define return to sport (RTS) and return to sport at previous level (RTSP) by the following:

- RTS, return to sport: Any athlete returning to any level of competitive sport.
- RTSP, return to competitive sport, at a level they were playing at preinjury or higher.

If studies only reported data on players who returned to the same level of play, the RTS and RTSP values were reported as the same proportion. If studies only reported data on players who were able to return to their sport, without clarifying the level, only RTS analyses were conducted.

**Statistical Analysis**

Percentage agreement and Cohen \( \kappa \) statistics were calculated to provide absolute agreement between raters for study inclusion. Descriptive statistics were calculated for all variables that were not included in meta-analysis (e.g. performance, return to sport times, complications, failures) (Microsoft Excel ©Microsoft Corporation, Santa Rosa, California).
Studies were included for meta-analysis by judging both clinical and statistical heterogeneity. Clinical judgment criteria involved assessment of similarity of populations, assessment context (e.g., athlete level, surgical procedure *a priori*). In addition, after approval using clinical judgment, studies were statistically pooled when ≥ 2 studies examined either the same athlete level or surgical procedures and return to sport variable (either RTS or RTSP). We calculated the pooled prevalence rate and 95% CI for outcome after various types of surgery and for athlete level (e.g. professional, collegiate, adolescent, recreational) when available. These were separated and further analyzed for RTS and RTSP.

To determine if differences across surgical treatment groups existed, a test of homogeneity of rates was used with a p<0.05 indicating significant differences between the pooled estimates of groups. Heterogeneity was assessed with Cochrane’s Q and I2. High heterogeneity was indicated by a Q p-value <0.10 and I2 >50%. There was no attempt to conduct simple sensitivity analyses by removal of studies and comparison to overall pooled estimates due to the limited number of categories with a meaningful number of studies. Instead, analysis focused on the comparison between the individual category pooled estimates in relation to the overall pooled estimates and changes in heterogeneity. Chi square analysis was used to perform within group comparison (comparator) differences in RTS for all studies. All analyses were conducted in Stata 14.0 (Stata Corp. College Station, Tx).

**RESULTS**

**Study Selection**

A total of 589 titles were identified through database and reference searches resulting in 22 included studies (Figure 1). Reasons for study exclusion at the full text screening are presented in Appendix 2. Conflicts of interest in included studies are reported in Appendix 3.

**Quality Assessment of Studies**

Eighteen studies reviewed were retrospective (cohort or case series), and as a result were either level 3b or 4 studies (Table 1). Four studies were prospective and were all level 4 (Table 1). Four studies were of low quality while the remaining 18 studies were of moderate quality. There were no high quality studies. The mean score on MINORS was 8.8 ± 2.1. Level of agreement between authors for study quality assessment was $\kappa = 0.73$ (95% CI: 0.63 to 0.85), for a substantial level of agreement.

**Study Characteristics**

There were a total of 617 athletes (87.9% males) evaluated for RTS criteria included in the 22 studies. Twenty-one articles provided detail on the athlete’s level of play with totals of 216 recreational athletes (16 studies), 210 professional/elite athletes (12 studies), 80 collegiate athletes (8 studies), 73 competitive athletes (5 studies), 24 amateur athletes (1 study), and 18 high school athletes (3 studies). The most frequently described sports included baseball/softball (227 athletes), rugby (46 athletes), tennis (40 athletes), and volleyball (36 athletes).

Twenty studies assessed the effects of arthroscopic surgery while one study looked at both non-surgical and arthroscopic intervention, and another study looked exclusively at non-surgical intervention. All studies looked at Type II SLAP lesions with the exception of two studies, encompassing a mix of Type II, III, and IV lesions and one study assessing Type VIII lesions. Fourteen
studies described coexisting pathology, with rotator cuff tears the most frequently described (11 studies) at a median rate of 34.8% (range 15%-76%). Seven studies reported concurrent rotator cuff repairs at a median rate of 11.8% (range 2%-75%).

Post-surgical complications were explicitly reported in ten studies with a total of six known adverse effects including two cases of broken anchors, two cases of suture abrasion, one case of subcutaneous suture granuloma removal, and one case of an upper extremity thrombosis. Post-surgical failures resulting in follow up operations were reported in 15 studies with a median rate of 3% (range 0%-13%).

### Diagnosis of Labral Pathology

Across all studies there was significant heterogeneity in the reporting of both indications for surgery, as well as determination of SLAP diagnosis for study inclusion. Specific to the diagnosis of the lesion, 16 studies reported imaging (MRI/MRA)
for all athletes of the study, while four studies reported basing diagnosis solely based upon clinical exam, including symptoms, special tests, and history. Another two studies reported no indication of how they identified and diagnosed athletes with SLAP tears. Regarding indication for surgery, only ten studies reported specific requirements to indicate surgical intervention, with eight studies reporting a trial of conservative treatment (including physical therapy) and two studies reporting “significant clinical findings”. The diagnosis of SLAP injury was not differentiated by mechanism or injury (acute/traumatic event vs chronic/overuse) in any of the included studies. All studies reported 100% of patients with a diagnosis of SLAP lesion according to their respective criteria, except Shah et al. who reported 81.4% with a SLAP diagnosis.

Return to Sport Proportions
The overall RTS proportion, regardless of level and type of intervention (e.g. surgical, non-surgical), was 93% (95% CI: 87% to 98%), with high heterogeneity (p = 0.00; I² = 83.46%). The proportion for RTSP was 72% (95% CI: 60% to 83%), again with high heterogeneity (p = 0.00, I² = 88.04%) (Figure 2), representing both surgical and non-surgical interventions (n = 20).

Surgical RTS (n = 21) proportion was 92% (86% to 97%), while surgical RTSP proportion (n = 19) was 74% (61 to 85%). Non-surgical RTS (n = 2) and RTSP (n = 2) proportions were 60% (49% to 71%) and 34% (24% to 45%) respectively.

Criteria for Readiness to Return to Sport
Nine studies reported some type of criteria for athletes to RTS with post-surgical time-frame the most prevalent criterion. Six months (n = 5 studies), and seven months (n = 1) were the most frequently utilized time-frames. Three studies reported that athletes were required to have pain-free function as well as pre-operative levels of strength and range of motion. None of these studies provided objective data that these criteria had been met. One study reported that athletes were required to complete a rugby-specific battery of tests to begin game play, and three studies required completion of an interval throwing program. No other studies provided any sport specific criteria for determination of RTS/RTSP. Completion of an interval throwing program was stated as a requirement in three of the ten studies examining baseball athletes. No studies provided specific information on additional requirements before beginning throwing programs and no studies reported if all baseball athletes met these timelines or had setbacks.

Reporting Athletes’ Post-Surgery Athletic Performance
None of the included studies reported on preinjury and post intervention athletic performance regardless of type of sport or athletic level.

Career Longevity
None of the included studies reported on post intervention athlete career longevity regardless of type of sport or athletic level.

Patient Reported Outcome Measures
Patient reported outcome measures (PROM’s) were reported in nineteen studies. All PROMs reporting post-surgical data for three or more studies are summarized in Table 2. Other PROMs included the Individual Relative Constant Score (CSIndiv), the Short-Form 36 (SF-36), the subjective shoulder value (SSV), the simple shoulder test (SST), the Cumulative Activities of Daily Living score...
sufficient detail for understanding of postsurgical rehabilitation. Additionally, only one study \(^37\) that required an interval throwing program to be completed by baseball players provided the citation of the throwing program that was performed.

**DISCUSSION**

The main finding of this systematic review and meta-analysis was an overall pooled RTS proportion of 93% and an overall pooled RTSP proportion of 72%. These proportions are similar to earlier findings.\(^5\) Analyzing RTS after injury is challenging for a variety of reasons.\(^6,11,42\) Analyzing RTS post SLAP injury has additional considerations ranging from different mechanisms of injury (acute vs chronic) to (CADL),\(^29\) the European Quality of Life measure (EuroQOL),\(^30\) and the modified Rowe Scoring system.\(^37\) Patient satisfaction was also reported for nine\(^4,20,23,24,27,31-33,39\) studies. Three studies\(^20,23,33\) quantified satisfaction on a visual analog scale, with athletes reported a mean of 86.4 ± 3.4% satisfied with the procedure. Seven studies\(^4,24,27,31-33,39\) also reported 82.2 ± 10.9% of athletes reporting their satisfaction as “good” or “excellent”.

**Post-Surgical Rehabilitation Guidelines**

Details regarding post-surgical rehabilitation timelines are provided in Table 3. Notably, only one study\(^33\) provided a citation to specifics of the rehabilitation plan utilized, and no studies provided sufficient detail for understanding of postsurgical rehabilitation. Additionally, only one study\(^37\) that required an interval throwing program to be completed by baseball players provided the citation of the throwing program that was performed.

**DISCUSSION**

The main finding of this systematic review and meta-analysis was an overall pooled RTS proportion of 93% and an overall pooled RTSP proportion of 72%. These proportions are similar to earlier findings.\(^5\) Analyzing RTS after injury is challenging for a variety of reasons.\(^6,11,42\) Analyzing RTS post SLAP injury has additional considerations ranging from different mechanisms of injury (acute vs chronic) to

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**Table 2. Mean Patient Reported Outcome Measures with both pre and post-surgical data**

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<td>KJOC</td>
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**Table 3. Postoperative Reporting of Rehabilitation Protocol**

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<tr>
<td>1 Week</td>
<td>Neri (’11)(^4)</td>
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<tr>
<td>2 Weeks</td>
<td>Boesmuller (’12), Boesmuller (’17)(^7)</td>
</tr>
<tr>
<td>3 Weeks</td>
<td>Neuman (’11), Yang (’08), Ide (’05), Kim (’02), Morgan (’98)(^13)</td>
</tr>
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<td>4 Weeks</td>
<td>Maier (’12), Friel (’10), Brockmeier (’09), Seroyer (’07), Cohen (’06), Samani (’01)(^13)</td>
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<td>6 Weeks</td>
<td>Park (’13)(^14)</td>
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<td>Time to Strengthening</td>
<td>Studies Reporting</td>
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<td>4-5 Weeks</td>
<td>Ide (’05), Kim (’02)(^27)</td>
</tr>
<tr>
<td>6-7 Weeks</td>
<td>Beyzadeoglu (’15), Brockmeier (’09), Yang (’08), Neumi (’08), Morgan (’98)(^13)</td>
</tr>
<tr>
<td>8-9 Weeks</td>
<td>Boesmuller (’12), Boesmuller (’17), Neuman (’11), Friel (’10), Samani (’01)(^13)</td>
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<tr>
<td>10-11 Weeks</td>
<td>Seroyer (’07)(^19)</td>
</tr>
<tr>
<td>12+ Weeks</td>
<td>Park (’13)(^14)</td>
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<tr>
<td>Time to Throwing</td>
<td>Studies Reporting (Only Baseball/Softball Players)</td>
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<tr>
<td>12 Weeks</td>
<td>Beyzadeoglu (’15), Neri (’11)(^14)</td>
</tr>
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<td>16 Weeks</td>
<td>Neuman (’11), Seroyer (’07), Yang (’08), Cohen (’06), Morgan (’96)(^13)</td>
</tr>
<tr>
<td>26 Weeks</td>
<td>Park (’13)(^14)</td>
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different demands of the sport the athlete is returning to (overhead throwing vs contact sport). It is perhaps fitting that the origins of SLAP injuries began with the description of a “dead arm” to describe the myriad of symptoms and presentations seen in these athletes. These extensive symptoms and prolonged pain are the most common reasons for athletes not returning to sport. Therefore, discussions around SLAP injuries, their management, and outcome expectations can be extremely multifactorial. Our goal was to systematically review, compile and report RTS proportions after SLAP injury, as well as discriminate RTS from RTSP.

Return to Sport
This review is the first to examine the discrepancy between RTS and RTSP, as well as report on nonsurgical intervention proportions. All but one study in this review reported RTSP as returning to the same level of sport. None of the included studies reported on the athlete’s performance upon RTS or RTSP. A previous review on ulnar collateral ligament surgical intervention reporting athletic performance post-surgery demonstrated decreases in athletic performance despite returning to similar level of sport. Various patient reported outcome measures (PROMs) were able to provide some assessment of post injury status in our review. Three studies examined KJOC scores after athletes had returned, with a mean score of these three studies being 77.1 ± 3.7. Both Fronke et al. and Kraetuler et al. found KJOC scores in asymptomatic baseball players to average >90. Wymore et al. found an average score of 84.4 in asymptomatic collegiate swimmers, while O’Brien et al. found overhead athletes successfully RTS from UCL reconstruction to have an average KJOC score of 77. While these limited results suggest more research is required, KJOC results suggest variability in an athlete’s ability upon RTS; some athletes (particularly baseball players) did not return at a level equal to their asymptomatic teammates post injury.

Diagnosis & Surgical Intervention
As outlined by Lesniak et al., SLAP tears can be extremely challenging to diagnose, particularly regarding their high prevalence rates in asymptomatic individuals. Likewise, there is little consensus on identifying the appropriate time to surgically intervene for an athlete with a known lesion. Diagnosis of a SLAP injury, as well as criteria utilized for surgical intervention, was limited in the included studies, further complicating the issue of management decision-making. The decision to undergo surgical intervention for SLAP injury is likely multifactorial, and, unfortunately, the current literature provides little guidance for the treating clinician to assist with this decision. Hopefully, future research will better identify the individuals for whom surgical intervention for SLAP injuries is the optimal intervention.

Criteria for RTS and Rehabilitation
Of particular importance for treating clinicians is the question of when to return an athlete to sport, as well as how best to guide their RTS progression. Many studies have been conducted on lower extremity testing batteries designed to clear athletes for RTS, particularly in athletes with anterior cruciate ligament (ACL) injury. Unfortunately, as outlined in the review, and seen in many athletic upper extremity injuries, limited consensus exists regarding RTS decision-making for any athlete returning from an injury. Table 3 concisely summarizes the tremendous variance in the post-surgical rehabilitation timelines for SLAP injury, providing little consensus from which the practicing clinician can seek guidance to structure their rehabilitation protocols. While no discernable differences in RTS rates or outcome measures were found when looking at time to activity, this is very likely due to the heterogeneity of demographics, diagnostics, and confounding factors previously discussed. Additionally, only 59% of the included studies reported RTS time-frame. Future high quality research is necessary to guide clinicians in the management of SLAP injuries.

Study Limitations
The primary limitation of the current study is the variability of competition level (recreational, competitive, etc.) of included athletes in the studies and not being able to discriminate RTS/RTSP proportions based on these levels. Variability was also seen with respect to how RTSP was reported. Analysis was only able to include RTSP proportions in studies that clearly delineated RTS and RTSP. While a professional overhead athlete is required to return
at a high level that is demanding to their injury, an acutely recreational athlete whose sport requires very little overhead motion may return at the same level with significant limitations in function outside of their sport.

Several other limitations were present based on the available literature. Unfortunately, there were no high-quality studies included in the analysis and four studies were of low quality. This low quality, combined with all studies being level 3B or 4, make the meta-analysis difficult to draw strong conclusions. Additionally, the search strategy being restricted to English language peer-reviewed studies only represents a possible publication bias.

CONCLUSION
Limited evidence suggests that less than three in four athletes return to their previous level of sport participation after SLAP injury intervention. Intervention success for an athlete with SLAP injury remains relatively unknown as only 59% of included studies clearly delineate RTS from RTSP and neither athletic performance nor career longevity were reported in any included studies. Future studies of higher quality are required for this determination.

REFERENCES


42. Reiman MP, Sylvain J, Loudon JK, Goode A. Return to sport after open and microdiscectomy surgery


**APPENDIX**

**Appendix 1.**

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<th>Term combinations</th>
<th>Description</th>
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**Appendix 2. Full Text Screen Reasons for Exclusion:**

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<tr>
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<td>Shoulder Surgeries for Pathologies Other Than Labral Injury</td>
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<tr>
<td>8</td>
<td>Surgical Technique Studies</td>
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<td>3</td>
<td>Less Than 80% of Subjects in Study Were Treated for Labral Injury</td>
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<td>3</td>
<td>Studies not Reporting Quantifiable RTS Data</td>
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<td>2</td>
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# Appendix 3. Potential Sources of Support (if reported in study)

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<td>&quot;The authors declare that there is no actual or potential conflict of interest in relation to this article.&quot;</td>
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<td>Boesmueller et al. (2017)</td>
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<td>&quot;The authors did not receive any outside funding or grants in support of their research or for preparation of this work. Neither they nor a member of their immediate families received payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, division, center, clinical practice, or other charitable or nonprofit organization with which the authors, or a member of their immediate families, are affiliated or associated. Institutional support was supplied only for statistical analysis in part by the Clinical and Translational Science Center Grant (NIH UL1RR024996) at Weill Cornell Medical College.&quot;</td>
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<td>Cohen et al. (2006)</td>
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<td>&quot;This study was supported by National Institutes of Health (NIH) grant T32 AR052272. The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.&quot;</td>
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<td>Funk &amp; Snow (2007)</td>
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<td>Ide et al. (2005)</td>
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<td>Kim et al. (2002)</td>
<td>&quot;The authors did not receive grants or outside funding in support of their research or preparation of this manuscript. They did not receive payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, educational institution, or other charitable or nonprofit organization with which the authors are affiliated or associated.&quot;</td>
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<td>Maier et al. (2012)</td>
<td>&quot;None of the authors has personal or financial conflicts of interest to disclose.&quot;</td>
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<td>Neri et al. (2008)</td>
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<td>Shah et al. (2016)</td>
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<td>Yung et al. (2008)</td>
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ABSTRACT

**Background:** Low back pain is believed to be a common complaint among dancers; however, a comparison across recent research is needed to support or disprove this assertion across genres.

**Purpose:** To determine the prevalence of low back pain and low back injury in ballet, modern, and hip-hop dancers through a systematic literature review. A secondary goal was to identify trends amongst dance genres, level of mastery, gender, and age, if possible.

**Study Design:** Systematic Review of the Literature.

**Methods:** PRISMA search strategy of terms relating to dance and low back pain was conducted within the Pubmed, MEDLINE, SPORTDiscus, Web of Science, and the archives of the Journal of Dance Medicine and Science databases between November 2017 and March 2018. Inclusion criteria were published articles that addressed low back pain or injury in ballet, modern, or hip-hop dance population. Exclusion criteria included studies relating to specific pathologies or studies that did not report specific dance genre. All included articles were assessed for quality using a modified grading evaluation and a Modified Newcastle-Ottawa Risk of Bias assessment.

**Results:** Twenty-five ballet articles, five modern, and three hip-hop articles met the inclusion criteria, for a total of 33 articles. Twenty-five of the 33 studies relied on a questionnaire to gather data. Risk of bias results ranged from 3-7/10 and quality of studies ranged from Good I to Limited III. Prevalence of low back pain seems relatively high in ballet dance (range: 20.3%-79% of total dancers are affected). Little research exists on the prevalence of back pain in modern or hip-hop dancers, but hip-hop dancers also seem likely to have low back pain (range: 46.6%-85.7% of total dancers are affected). Low back injuries are also present in ballet (range: 2.1%-88% of total injuries), modern (range: 8.6%-21.6% of total injuries), and hip-hop (range: 26.3%-69.6%).

**Conclusion:** Ballet dancers seem to be at risk for low back pain or injury independent of gender, age or level of mastery; however, there is not enough evidence to draw any conclusions about modern dancers or hip-hop dancers and their risk for low back pain/injury currently. Future higher-level studies are needed with reduced risk of bias.

**Level of Evidence:** 2a

**Keywords:** Lumbar pain; Professional dance; Sports injury
INTRODUCTION

If a dancer’s body is affected by injury, they cannot fulfill their potential as a dancer. Chronic injuries can compromise a dancer’s ability to dance for the rest of their lives. In the last 30 years, most professions have moved towards a trend of incomplete retirement.1 This is particularly true for dancers, where much of a dancer’s identity is tied to their ability to stay connected to dance throughout their lifetime, and injuries can threaten this identity.2 Many dancers continue in other aspects of the dance industry once they retire from professional performance, and with a retirement age in their late 20’s/early 30’s,3 this is similar to other types of sport, and significantly earlier than national mandatory retirement ages.4 Keeping dancers injury-free throughout their career and during their partial retirement is central to supporting dancers.

Low back pain (LBP) is a significant problem worldwide,5 with prevalence in the general population suggested to have a one-month prevalence of 23.2 +/- 2.9%5 and a general prevalence to be 9.4% in 2010 and on the rise.4,6 Data suggest that dancers show an increased prevalence of LBP in comparison to those in the general population7 who exercise less often. Much of existing literature on low back pain and dance-related injury does not subdivide the study population by genre, often using the umbrella term ‘dancers’ or combination labels like ‘modern and ballet dancers’. These terms do not give context to the main dance genres that are studied and prevents comparisons. Current literature also prioritizes female professional ballet dancers as the subjects of study, with few studies on modern and hip-hop dancers. The movement demands of these three dance genres are not the same, with several researchers noting differences between ballet and modern dance.8 Thus, it cannot be assumed that the prevalence of low back pain or injury in one dance genre is identical for all dance genres.

Dance has a high rate of injury,9-18 particularly amongst professional ballet dancers.19-21 This injury rate has been linked to short professional careers that often end before the dancer reaches 40 years of age,22,23 although the field of dancer retirement has been under-researched.24 Lower extremity injuries are the most common, followed by neck/trunk/spine injuries.10,14-17,20 It is difficult to assess mean incidence rates across multiple studies, but LBP in dancers is an ongoing injury that has been documented to have a lasting negative effect on dancers, even after they have stopped dancing professionally.25 Dancers of all ages, sex, proficiency levels, and genres may experience low back pain and injury. A number of literature reviews, particularly those that center on ballet dancers, have cited the prevalence of LBP to be anywhere from 3%-23%15 to 12%-75%16 with a calculated prevalence of 14%.29

Studies on LBP do not always agree on a standard definition of what LBP is, and this is also true for LBP research on dancers. MeSH database defines “low back pain” as, “Acute or chronic pain in the lumbar or sacral regions (MeSH Unique ID: D019567).”28 The MeSH database does not have a definition for low back injury (LBI), but defines “back injury” as, “General or unspecified injuries to the posterior part of the trunk. It includes injuries to the muscles of the back (MeSH Unique ID: D017116).”28 A modified Delphi study published in 2008 suggested that questionnaires that address LBP should ask for a recall of no more than four weeks, to clarify with subjects whether this low back pain limited or changed daily activities for more than one day, and to include an anatomical diagram that highlights the low back.29

Understanding the prevalence of LBP and LBI in individual dance genres can assist dance trainers in understanding if their specific population is at risk, particularly if there are additional trends of risk amongst skill level, gender, or age. Preventative training and interventions can then be established with an aim of decreasing the prevalence and, as a result, increasing dancer quality of life and career longevity. Therefore, the primary objective of this systematic review was to determine prevalence of low back pain or injury in ballet, modern, and hip-hop dancers. The secondary objective was to identify whether there are trends in the data for dance genre, level of mastery, gender and age, as able.

METHODS

Search Methodology

This review was conducted between November 2017 and March 2018 using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses
(PRISMA) method. A search was conducted of titles and abstracts in Pubmed (1966 to March 2018), MEDLINE (1946 to March 2018), SPORTDiscus (1983 to March 2018), Web of Science (1900 to March 2018), Journal of Dance Medicine & Science online archives (1997 to March 2018) databases using six permutations of the MeSH keyword “back pain” or “injury” and text words, as shown in Table 1.

A hand search of the reference lists of identified studies was conducted. A single investigator conducted the search actions and initial screening processes. Three articles that did not have an accompanying English translation were assessed with the help of translation applications: two in Portuguese and one in German.

Inclusion criteria were:
- The article had to address low back pain or injury in a ballet, modern, or hip-hop dance population
- The “Ballet” genre included sub-genres classical, contemporary, and neo-classical ballet dance
- “Modern” dance included sub-genres related to both classical modern (i.e. Graham technique) and newer post-modern
- “Hip-hop” incorporated studies on its subgenres, most notably breaking, locking, and popping

Exclusion criteria were:
- Participants from dance genres other than ballet, modern, or hip-hop dancers
- Participants were not specified or separated by dance genre
- No testing for back pain or injury (performance measures alone were not satisfactory)
- Examining back pain as related to a specific pathology
- Duplicated data published in different publications,
- Case studies or series
- Non-primary sources (i.e., literature reviews)
- Grouping the lumbar spine with other areas of the body
- Articles without English translated titles (those articles with titles translated to English were included, even if the article itself required some translation)

### Initial Screening

The electronic database search yielded 639 articles, combined with 41 additional records identified through other sources, such as references lists, to produce 680 total articles. Three hundred and thirty remained after duplicates were removed, excluding 290 of the remaining articles for not meeting inclusion criteria (Figure 1). Differences in the categorization of “genre name” were addressed by the inclusion of sub-genres; for example, Graham or

| Table 1. Search Methodology Keywords and Fields Used to Locate Articles |
|-----------------|-----------------------------------------------|
| In title:       | All fields, MeSH terms:                      |
| dancers         | "back pain"                                  |
| dancers         | back pain                                    |
| dancers         | lumbar pain                                  |
| dance           | back pain                                    |
| dancers         | lumbar injury                                |
| dancers         | "back injury"                                |

Please note that both "injury" and the plural term "injuries" was included automatically by the search engines, or manually searched when not automatically included by the databases’ search engines.
Horton were classified as modern, and Breakers, Poppers/Lockers, or New Schoolers were categorized as hip-hop. In contrast, studies that used the umbrella term “dance”, instead of specifying a main discipline or exposure hours, were excluded.

**Full-Text Assessment Procedure**

After the initial screening of titles and abstracts, two researchers independently performed a full-text assessment of the remaining 40 articles, leading to the exclusion of seven more articles. Studies were assessed for their quality based on the Academy of Nutrition and Dietetics (Academy) Research Committee's 2013 adaptation of Greer et al.'s original evidence grading strategies, referred to ‘ADA scoring system’ for the remainder of this article. There were five grades given to the articles once examined: Good I, Fair II, Limited III, Expert Opinion Only IV, Grade Not Assignable V. A data-extraction sheet was utilized for full-text assessment, the results of which were compiled into a spreadsheet and then processed. A third researcher acted as a third reviewer for any disputed scores. Risk of Bias was measured using a modified Newcastle-Ottawa assessment.

**RESULTS**

**Included Studies**

The final articles included 25 ballet articles, five modern, and three hip-hop for a total of 33 articles. Sixteen articles studied at least one population of current professional ballet dancers. The incidence of LBP and LBI varied extensively, even between the scarce modern and hip-hop results. Summary tables of articles examining LBP/I that were included in this study can be found in Appendices A, B, and C, for ballet, modern, and hip-hop dancers, respectively.

**Study Design and Risk of Bias**

Twenty-five of the 33 studies collected self-reported data via questionnaire. Thirteen studies included the use of medical records and six used physical screenings to determine incidence of pain or injury to the low back. Thirteen studies utilized multiple data collection methods, often both a questionnaire and the use of medical records. Few studies measured back pain identically, although most used a modified retrospective survey approach across a set amount of time (i.e., “Have you had back pain within the last week? Month? Year?”). The injury definitions of “low back pain” or “low back injury” varied, with studies describing pain as “mechanical low back pain”, or defining injuries to this area as ‘lumbar lesions’.

Studies that examined the duration of pain over the course of a dancer's career used the terminology “lifetime history of low back pain” or “lifetime prevalence of low back pain”.

A summary of the results of the Risk of Bias assessment can be found in Table 2. An adapted Newcastle-Ottawa method specific to cross-sectional studies was used, which grades each study out of ten possible points: five for population selection method, two for comparability, and three for the outcome methods. Only five studies scored less than five, however, no study scored higher than seven. Twenty-five studies relied on non-random sampling methods: convenience sampling (twenty-five studies), snowball sampling (two studies), volunteer sampling (five studies), or a combination; one study did not describe their sampling technique at all. The lack of random sampling techniques limited the robustness of the reviewed research and prevented any study from gaining a full score.

**Data Reporting**

Conclusive results for the prevalence of LBP and/or LBI were unable to be calculated because of the difference in data reporting between studies. Sixteen studies reported how many dancers of the total population studied complained of low back pain/injury (LBP/I), while the other

<table>
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<th>Table 2. Risk of Bias Reporting Summary (modified Newcastle-Ottawa Method) in Articles examining Low Back Pain and Injury in Dancers</th>
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<td><strong>Stars (out of 10)</strong></td>
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<tr>
<td>6</td>
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<td>5</td>
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<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
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</table>
eighteen studies\textsuperscript{11,32,41–47,50–51,53-56,60-61} calculated what percentages of their total pains/injuries were LBP/I.

**Ballet Dancers**

Twenty-five studies\textsuperscript{11,13,21,25,30-32,36–53} examined LBP/I in ballet dancers. Of the 25 articles, six scored grades of “Good I”, sixteen scored “Fair II”, and three scored “Limited III” using the ADA scoring system. Risk of Bias scores ranged from 3-7/10 and averaged 5.6/10. Sample sizes ranged from 24 participants\textsuperscript{51} to 476 participants,\textsuperscript{11} with three studies\textsuperscript{30,31,52} having female-only populations, and seven studies\textsuperscript{11,21,36-37,42-43,45} dividing their LBP/I results by gender. Quantifiable activity level was not reported for seven studies,\textsuperscript{25,38-39,42,46,51-52} and those that did provide activity level, typically in hours per week, varied substantially from one another (the range for those that reported activity level in hours per week was 3.9 +/- 1.5 hours/week to 40-50 hours/week).

Eighteen\textsuperscript{21,25,30-32,36–40,44-49,51-52} of these studies used questionnaires as a data collection tool. Studies could not be meta-analyzed due to the differences in both collection methods and data reporting (Table 3). Collectively, the studies indicate that ballet dancers experience LBP, with an average of 57% LBP prevalence (range: 20.3%-79%), as well as LBI (range: 5.3%-22.6%). The number of ballet dancers with LBP specifically in these studies trended towards two out of every three dancers experiencing LBP (median: 62%, mean: 57%).

**Modern Dancers**

Five studies\textsuperscript{54–58} examined LBP/I in modern dancers. Of these articles, two scored “Good I” and three scored “Fair II” using the ADA scoring system. Risk of Bias scores ranged from 4-7/10 and averaged 5.6/10. Sample sizes ranged from 22 participants\textsuperscript{57} to 444 participants,\textsuperscript{54} with one study\textsuperscript{55} dividing their LBP/I results by gender. Quantifiable activity level was not reported for one study.\textsuperscript{56} Four\textsuperscript{55-58} of these studies used questionnaires as a data collection method. Studies could not be meta-analyzed due to the differences in both collection methods and data reporting (Table 4). The five studies, which all examined a population of modern dance students, seem to agree that LBP/I exist, although there is a serious dearth of studies. The results from these studies trend towards being lower than those of the ballet studies, with LBP prevalence being reported as 27.3% of dancers and LBI prevalence ranging from 8.6%-21.6% of total injuries.

**Hip-Hop Dancers**

Three studies\textsuperscript{59-61} examined LBP/I in hip-hop dancers. All three articles scored “Fair II” using the ADA scoring system. Risk of Bias scores ranged from 5-7/10 and averaged 6.3/10. Sample sizes ranged from 42 participants\textsuperscript{61} to 232 participants,\textsuperscript{60} with one study\textsuperscript{59} having an all-female population, and another study\textsuperscript{60} having an all-male population. Quantifiable activity level was not reported for one study.\textsuperscript{60} All three of these studies used a questionnaire as their data collection method. Studies could not be meta-analyzed due to the differences in both collection methods and data reporting (Table 5). The three studies seem to agree that LBP/I exist, with a mean LBP prevalence of 61.1% prevalence (range: 46.6-85.7%) and LBI prevalence of 49.0% (range: 26.3%-69.6%), which are much higher than the modern dance studies, with values closer to that of the ballet dance studies. The number of hip-hop dancers with LBP specifically trended towards two out of every three dancers experiencing LBP (median: 56.0%, mean: 61.1%).

**DISCUSSION**

The primary findings of the present study indicate that not enough LBP/I data exist, particularly for...
modern and hip-hop dancers, and that clear injury definitions and more descriptive statistics surrounding participant demographic (gender, exposure hours, primary dance genre) are needed in order to be able to complete additional comparisons. Many studies used professional ballet dancers as their population of study, and very few studies had modern or hip-hop dancers as participants. There was a large range of prevalence values between studies, and a high risk of recall bias with many studies relying on questionnaires for data collection. The current study found risk of bias scores to be relatively low, however, with no study scoring higher than seven out of ten, mainly due to the reliance on non-random sampling methods. This limitation was present in the majority of dance research on LBP/I, and these researchers hypothesize this is due to the convenience of having many dancers present as part of a dance company or university dance program; collecting data becomes simpler and the participation rate presumably higher when all of the population is in the same place at the same time, or participation in the study can be supported by a company or program director. However, this convenience pitfall also reduces the robustness of the research and should be reduced in future research to adequately address risk of bias. This will lend confidence to the acquired results, and these researchers predict that a reduced risk of bias will affect the large range of results for LBP/I in dancers over time.

Differences in Data Collection and Presentation
Despite the limited robustness and large range of results, it would seem that ballet and hip-hop dancers are at moderate risk for LBP/I. Direct comparison between studies was prevented by heterogeneity between studies. Data collection methods for pain/injury data varied, with sixteen studies reporting the number of pains/injury and seventeen studies reporting the number of people with pain/injury across all three dance genres in the present reviews. For example, twelve ballet studies surveyed how many dancers had back pain, while four ballet studies surveyed how many instances of back pain occurred in a certain time frame; this made processing the data difficult without subdividing it for purposes of pooled statistical comparison. Vast differences in collection and reporting methods prevented even the most general comparisons to be made about the prevalence of back pain. Variation in types of questionnaires, screening methods, collection methods, interview questions, and differing injury definitions made determining prevalence difficult.

Baker et al. discussed the contrast between self-reported and reported injuries in contemporary dance students, and suggest that there is a difference in how dancers and physiotherapists classify injury. However, Ramel et al. administered a Self-Estimated Functionality Inability because of Pain (SEFIP) survey for areas of pain to ballet dancers, and then completed a test battery to confirm the results of the survey. They found that there was good agreement between where the dancers cited pain on the survey and where medical professionals identified areas of pain or weakness during the test battery.

Additionally, some research included in the current study did not include any quantitative level of dance activity, which further complicates directly comparing any of the studies. For example, Ramkumar et al. reported that their professional ballet population danced an average of 27.5 hours per week (injury incidence of 0.65 per 1000 hours), excluding dress rehearsals and performances. In comparison, Arendt et al. found that most of their professional ballet population danced 45-50 hours per week (number of weeks per year was unspecified in the study, but assuming a 44 week contract, injury incidence per 1000 hours would be 3.27-2.95). Each studio, university, conservatory, and professional dance company has differing schedules and demands, so it is unsurprising that the level of activity might differ, even amongst professional ballet dancers. As developing research suggests, there may be a correlation between hours of dance activity and rate of injury. Thus, noting the dance exposure hours instead of, or in addition to, the experience level of a given dance population will allow for more direct comparisons between populations.

Table 5. Reporting Methods in studies examining Low Back Pain and Injury Reports in Hip Hop Dancers

<table>
<thead>
<tr>
<th>Data reported as:</th>
<th>Low back pain or injury values:</th>
<th>Range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>People with low back pain (1)</td>
<td>46.6%, 55.9%, 58.2%, 85.7%</td>
<td>46.6%-85.7%</td>
</tr>
<tr>
<td>Number of pains in the low back (9)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>People with low back injury (1)</td>
<td>69.6%, 26.3%</td>
<td>26.3%-69.6%</td>
</tr>
<tr>
<td>Number of Injuries to the low back (1)</td>
<td>7%, 8%</td>
<td>7%-8%</td>
</tr>
</tbody>
</table>

*parentheses indicate number of articles who reported in this way.
Overall, dancers appear to be at significant risk for LBP, and an increased risk of LBI, although the risk seems higher for dancers who specialize in ballet and hip-hop rather than modern dancers. Of greatest concern to professionals is identifying if their dancers have increased risk. By addressing trends in LBP/I within levels of mastery, age, and gender, it may be possible to determine those dancers who may be at risk of LBP/I before the onset of LBP/I.

SECONDARY OBJECTIVES

Level of Mastery
Secondary objectives of this review included assessing trends in LBP and LBI along the dancers’ level of mastery. Overall, research across varied sport populations seem to agree that athletes who have increased exposure or intensity during participation have more injuries than those who do not.63 Studies of athletes like gymnasts seem to suggest that LBP is linked to increased exposure hours,64 leading to the hypothesis that dancers may also see this trend. No trends could be definitively stated for LBP/I and level of mastery from the current study. From the limited amount of research available, professional hip-hop dancers seem to be at more at risk than those with less mastery, yet both modern and ballet results were too inconsistent to present any trends.

When possible, the original researchers’ categorizations for mastery/experience were used. Otherwise, three arbitrary categorizations were used, based on the amount of dance (rehearsals, classes, performances) completed on an average week that fit the majority of full-text articles: Student (<15 hours per week), Pre-Professional (>15 hours per week), and Professional (hired by a “professional company”).

Ten studies did not provide a measure of dance exposure or typical workload, thus were unable to be categorized. The studies that did specify exposure varied in their classification of these exposures; for example, professional dancers were reported to have between 27.541 to 45-5033 hours of ballet training per week, or only stating they were “professionals with a full workload.”39

Some studies reported a “teacher” category that was separate from both students and professionals.

Previous authors have indicated differing demands on the body between dance classes, rehearsals, and performance,65 and researchers providing the ratio of these three items could allow for comparison across multiple studies in the future. Further research should include demographics that give a sense of the rigor and duration of dancing, not just titles like ‘student’ or ‘professional’, to account for the differences in dance programs, performance seasons, and dance genres. This supports the need for dance activity levels and exposure hours to be included in future research.

Age
Reviews of sport literature agree that children and adolescents seem to be at risk for sport-related injuries,66 with theories that physical and physiological differences many account for these high rates, and decreasing their vulnerability with age and maturation.67 However, for LBP specifically, the specific sport population being studied changes the relationship between LBP/I risk and age. Several studies have found that young athletes generally are at a higher risk of LBP than adults, although the causes may differ.68 This contrasts with gendered sports like rhythmic gymnastics, Dance Sport, and similar disciplines where there is an increased risk of LBP with age.69-72

Studies did not specify the age range of those dancers who either became injured or had endured/still endure back pain, thus any trends between age and risk for LBP/I were unable to be discerned. Demographics for the general population were provided, but none for those dancers that actually presented with LBP or LBI. This again calls for more research into age and LBP/I for dance in general, and specifically ballet, modern, and hip-hop dance.

Gender
None of the eligible hip-hop dance studies provided separate data on males and females with LBP/LBI. Additionally, this study was unable to discern clear gender trends amongst the modern dance studies, as only one reported data separately. Sport research does not seem to have analogous low back pain or injury research; most studies compare males and females from different sports. Often sport injury reporting aggregates multiple sports (such as combining dancers and gymnastics into the same
dancers of any genre, but especially if that dance discipline tends to have differences in expectations for a “male role” and a “female role”.

Limitations & Future Recommendations

There are limitations to this study. DanceSport, Flamenco, and other such dance populations were not included in this study, although some research into those dance genres does exist. Studies that focused on degenerative pathologies, such as spondylosis or degenerative disk disorders were excluded; the causes of low back pain in dancers are assumed to be multi-faceted, and thus are not addressed in most of the research into back pain and injuries. While the researchers recognize that degenerative pathologies most likely constitute some of the dancers who claimed to have back pain or injury within the included studies, a skew in these data may have occurred due to the exclusion of chronic diseases. Future studies should include the time frame over which subjects are assessed for pain/injury, and researchers should obtain both the number of complaints and how many people have these complaints to aid comparison across multiple studies on this topic. For example, reporting that 30 injuries out of 100 injuries that occurred in a dance performance season were LBI, as well as reporting that 20 out of the 30 total dancers who participated had LBI. While this may seem redundant, reporting both values aids in comparison across studies when trying to identify prevalence. As noted, the majority of studies used in this review included pain or injury questionnaires. Questions such as, “Have you had back pain in the last year?”, asked dancers to recall experiences, relying on their memory which can be unreliable, particularly as the level of detail pertaining to injuries increases. Level of evidence would increase if reliance on memory decreased, however, the discrepancy between self-reporting and medical record reporting needs to be addressed; and the validity of performing either a questionnaire or viewing medical reports when trying to assess the “true” prevalence of back pain should also be considered.

Further studies would benefit from dividing their data by dance exposure hours or similar measurement rather than arbitrary categories like “professional” or “pre-professional”, since agreement on

Aggregating multiple sports or injury sites would negate any differences between males and females in the same sport or in sports that have “gendered roles". Miletic et al. found that male international DanceSport dancers had more hip pain than female dancers, suggesting differences in male and female roles. Male and female gymnasts seem to display anthropometric differences and may be considered to have “gendered roles”, as male and female gymnasts participate in different gymnastic events. For dance research, DanceSport seems to indicate anthropomorphic gender differences as well, but injury results reported by gender are scarce, as standardized measures and overall research into DanceSport injuries are lacking.

Dance research also lacks standardization; Baker and researchers, indicated that three of their 56 female injuries had “lower back injuries" and three of their 14 male injuries had “lower back injuries" as reported by the dancers; however, eight of 52 injuries and one out of 11 injuries were reported by physiotherapists for that same time period. Because the dance students and the physiotherapists in that study were not perfectly aligned in their injury definitions, it is difficult to make definitive statements on the role that gender plays in putting modern dancers at risk for LBP/LBI.

Seven of the 25 ballet studies differentiated between males and females; those studies which did found very little discrepancy, which was unexpected, due to the popularity of gendered roles in ballet, as many ballet pieces traditionally have a male and female role with different physical requirements. However, due to the significant number of women in ballet as compared to men, the male sample sizes were noticeably smaller than their female counterparts. More research into gender differences should be included in future studies of injury and pain in
these terms is low even within the same dance genres. Further research in genres other than ballet, including modern and hip-hop dance, are required to provide a comprehensive understanding of LBP/I.

In order to better compare outcomes of future research in dance, the authors suggest the following best practices:

- Use clear injury definitions, and report both the number of complaints and how many people have these complaints.
- Include non-ballet populations of study.
- Report time dancing in objective epidemiological measurements, such as exposure hours.
- Address possible discrepancies between self-reported and reported injuries, if applicable.
- Record gender differences, particularly if the dance genre utilizes gendered roles.
- Include the time frame used for assessing pain/injury and limit the length of time participants are asked to recall information if using a questionnaire format.
- Gathering data on both low back pain and low back injury is ideal.

CONCLUSIONS
The included studies in this review suggest that the prevalence of LBP/I seems relatively high in ballet dancers (LBP range: 20.3%-79% of total dancers are affected; LBI range: 2.1%-88% of total injuries), not as likely in modern dancers (LBP reported by one study as 27.3% of total dancers are affected; LBI range: 8.6%-21.6% of total injuries), and possibly a higher risk in hip-hop dancers (LBP range: 46.6%-85.7% of total dancers are affected; LBI range: 26.3%-69.6% of total dancers are affected), although not enough high-quality research exists on the subject to date. Future studies need a higher level of evidence and a reduced risk of bias. The current study's results also suggest that ballet dancers are at risk for LBP/I independent of gender, age or level of mastery. There is not enough evidence to draw any conclusions about modern dancers or hip-hop dancers and their relationship to LBP/I currently.

REFERENCES
14. Jacobs CL, Hincapié CA, Cassidy JD. Musculoskeletal injuries and pain in dancers: a


## Appendix A: Summary of Articles examining Low Back Pain and Injury in Ballet Dancers

<table>
<thead>
<tr>
<th>Article Title</th>
<th>First Author &amp; Year</th>
<th>Design</th>
<th>Collection Methods / Intervention</th>
<th>Level of Evidence</th>
<th>Sample size, mean agespan</th>
<th>Terms used</th>
<th>Level of Evidence &amp; Average Dance Participation</th>
<th>Relevant Outcomes: Total with LBP (with other studies)</th>
<th>Makes with LBP</th>
<th>Paralyses with LBP</th>
<th>Notes &amp; Limitations</th>
<th>GRADE score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics and prevalence of musculoskeletal injury in professional and non-professional ballet dancers</td>
<td>Costa et al., 2018</td>
<td>Retrospective case-control study</td>
<td>Questionnaires; professional dancers to assess presence, location, and mechanism of injury</td>
<td>4</td>
<td>n = 110 (88 professional, 22 non-professional)</td>
<td>2.0-5.7 years</td>
<td>Pre-professional; 3.8-6.0 hours/week</td>
<td>35/53, 22% professional women explained the most affected by injury</td>
<td>15/22, 68%</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>National survey to evaluate musculoskeletal health in ballet dancers in the United Kingdom</td>
<td>Smith et al., 2017</td>
<td>Retrospective cross-sectional study</td>
<td>Questionnaires; online survey of retired and ballet dancers in the UK</td>
<td>4</td>
<td>n = 48 (14 left, 34 right); mean 31 years (IQR 48-92)</td>
<td>Pain in the lower back</td>
<td>Retired professionals; no activity level given</td>
<td>24/46, 71% retired dancers</td>
<td>5/23, 21% with injury, 24% with non-injury, 24% with injury</td>
<td>1/25, 0%</td>
<td>Not all data reported/completed, bias of non-reporting</td>
<td>3</td>
</tr>
<tr>
<td>Musculoskeletal injuries in young ballet dancers</td>
<td>Leanderson et al., 2011</td>
<td>Retrospective cohort study</td>
<td>Medical records; longitudinal study</td>
<td>4</td>
<td>n = 472 (169)</td>
<td>Pain in the lower back</td>
<td>-</td>
<td>45/847, 5.5% of dancers experienced injury, 15% of dancers</td>
<td>22/179, 6%</td>
<td></td>
<td>-</td>
<td>Fa III</td>
</tr>
<tr>
<td>Injury patterns in elite pre-professional ballet dancers and the utility of screening programs to identify risk characteristics</td>
<td>Gambardella et al., 2008</td>
<td>Retrospective cohort study</td>
<td>Questionnaires; medical records; clinical examination</td>
<td>4</td>
<td>n = 333 (293)</td>
<td>History of injury in the lower back</td>
<td>History of injury</td>
<td>33/177, 19%</td>
<td>9/21, 43%</td>
<td>1/12, 8%</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Verstahrungen und -scheinungen im professionellen Tanz</td>
<td>Alten et al., 2003</td>
<td>Retrospective cohort study</td>
<td>Questionnaires; medical records; clinical examination</td>
<td>4</td>
<td>n = 77 (42)</td>
<td>&quot;Lower back pain&quot;</td>
<td>History of injury</td>
<td>49/957, 68% common disorders associated with back pain</td>
<td>2/25, 0%</td>
<td></td>
<td>-</td>
<td>Fa I</td>
</tr>
<tr>
<td>The prevalence and impact of low back pain in professional and pre-professional ballet dancers: A prospective study</td>
<td>Cesar et al., 2018</td>
<td>Prospective cohort study</td>
<td>Questionnaires; screenings; medical records</td>
<td>4</td>
<td>n = 168 (129)</td>
<td>Low back pain</td>
<td>History of injury</td>
<td>5/119, 78%</td>
<td>4/129, 14%</td>
<td>-</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Analysis of the relationship between low back pain and muscle strength imbalances in ballet dancers</td>
<td>Aquino et al., 2010</td>
<td>Cross-sectional cohort study</td>
<td>Questionnaires &amp; screenings; test battery</td>
<td>4</td>
<td>n = 62 (62)</td>
<td>&quot;Mechanical lumbar pain&quot;</td>
<td>Pre-professional: 3 hours/week</td>
<td>No significant relationship was identified between lumbar muscle weakness and the prevalence of LBP</td>
<td>2/142, 0%</td>
<td></td>
<td>-</td>
<td>Fa II</td>
</tr>
<tr>
<td>Validation of a Pain Questionnaire (SPFP) for dancers with a specially created test battery</td>
<td>Ramel et al., 1999</td>
<td>Cross-sectional study</td>
<td>Questionnaires &amp; screenings; test battery</td>
<td>4</td>
<td>n = 28 (17 male, 11 female)</td>
<td>Low back pain</td>
<td>Pre-professional: 3 hours/week</td>
<td>The SPFP was found to be valid and reliable for detecting back pain in dancers</td>
<td>2/142, 0%</td>
<td></td>
<td>-</td>
<td>Fa II</td>
</tr>
<tr>
<td>Life history and point prevalence of low back pain in professional and pre-professional dancers</td>
<td>Dawn et al., 2017</td>
<td>Cross-sectional study</td>
<td>Questionnaires &amp; screenings; test battery</td>
<td>4</td>
<td>n = 110 (91)</td>
<td>&quot;Low back pain&quot;</td>
<td>Pre-professional; no activity level given</td>
<td>No significant association was found between LBP and physical activity</td>
<td>15/18, 78%</td>
<td>0/51, 72%</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>

* Fa I: fair; Fa II: poor; Fa III: very poor
### Appendix A. Summary of Articles examining Low Back Pain and Injury in Ballet Dancers. (Continued)

<table>
<thead>
<tr>
<th>Study Title</th>
<th>Authors/Year</th>
<th>Type of Study</th>
<th>Sample Size</th>
<th>Follow-up</th>
<th>Methodology/Findings</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Dynamics Are Improved in Ballet Dancers with Back Pain But Improves with Imagery</td>
<td>Giddey et al., 2015</td>
<td>Non-RCT, cohort study</td>
<td>n = 36 [15, 95], 24.4 years</td>
<td>&quot;low back pain&quot;</td>
<td>Made assumptions about classification of the trunk muscles in order to simplify estimation of trunk parameters. Consequence sampling limited the size of the path-free group.</td>
<td>Limited III</td>
</tr>
<tr>
<td>Morphology of the abdominal muscles in ballet dancers with and without low back pain: A magnetic resonance imaging study</td>
<td>Giddey et al., 2014</td>
<td>Observational study</td>
<td>n = 31 [17, 47], 23.3 years on average, 24.4 years average</td>
<td>&quot;pain in the region of the lower back&quot;</td>
<td>The preliminary evidence of compromised behaviour of TA muscles in LBP provides a foundation, to move forward with more research.</td>
<td>Poor II</td>
</tr>
<tr>
<td>Reappraisal musculoskeletal pain in professional ballet dancers: a 10-year follow-up</td>
<td>Ramapriyakulakorn et al., 1999</td>
<td>Cohort Study</td>
<td>n = 45 [34, 56], 22.31 (20-28) years</td>
<td>&quot;pain, reported in the low back&quot;</td>
<td>Participated in 10-RM General Disability Questionnaire, no significant difference in low back pain between groups.</td>
<td>Fair III</td>
</tr>
<tr>
<td>Injuries in a Professional Ballet Dance Company A 10-Year retrospective study</td>
<td>Ramkumar et al., 2015</td>
<td>10-year retrospective study</td>
<td>n = 153 [71, 27.5 years</td>
<td>&quot;lumber strain injury&quot;</td>
<td>The data revealed that dancers who sustained one or more low back pain injuries were more likely to quit than those who did not.</td>
<td>Good I</td>
</tr>
<tr>
<td>Dancer’s Injuries in professional ballet: injury-based differences among ballet disciplines</td>
<td>Sobrino et al., 2015</td>
<td>Cross-sectional study</td>
<td>n = 145 (71], 25.79 + 5.69 years</td>
<td>&quot;mechanical low back pain&quot; &amp; &quot;lumbar muscle injury&quot;</td>
<td>The prevalence of injuries in classical ballet and among women was significantly higher than in non-classical ballet and among men.</td>
<td>Good I</td>
</tr>
<tr>
<td>The effect of spinal and pelvic posture and mobility on back pain in young dancers and non-dancers</td>
<td>McMessel et al., 2002</td>
<td>Cross-sectional study</td>
<td>n = 120 (62 dancers, 58 non-dancers)</td>
<td>&quot;low back pain episodes in the last year&quot;</td>
<td>No significant difference observed in posture or mobility between groups.</td>
<td>Fair III</td>
</tr>
<tr>
<td>A prevalence de dor em balermnas classicas: The prevalence of pain in classical ballet dancers</td>
<td>Saltets et al., 2010</td>
<td>Retrospective cross-sectional study</td>
<td>n = 36 [30, 45], 4.5 years</td>
<td>&quot;dor de nevoio lombar&quot;</td>
<td>Almost 20% experienced low back pain.</td>
<td>Limited III</td>
</tr>
</tbody>
</table>
### Appendix A. Summary of Articles examining Low Back Pain and Injury in Ballet Dancers. (Continued)

<table>
<thead>
<tr>
<th>Study Title</th>
<th>Authors, Year</th>
<th>Study Design</th>
<th>Sample Size</th>
<th>Inclusion Criteria</th>
<th>Methods</th>
<th>Injury Demographics</th>
<th>Findings</th>
<th>Impact</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballet injuries: injury incidence and severity over 1 year</td>
<td>Allen et al., 2017</td>
<td>Prospective, descriptive single-cohort study</td>
<td>n = 52 (27 F, 25/6 M) years</td>
<td><em>p &lt; 0.05</em> for low back pain; <em>p &lt; 0.01</em> for lumbar muscle strain/tear</td>
<td>2</td>
<td>Professional; 30/35 hours/week</td>
<td>Significant increase in low back pain over the study period.</td>
<td>The study sample included dancers from a major ballet company.</td>
<td>Good II</td>
</tr>
<tr>
<td>Musculoskeletal injuries in the Norwegian National Ballet: a prospective cohort study</td>
<td>Byhring et al., 2002</td>
<td>Prospective cohort study</td>
<td>n = 47 (27 F, 29/20 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Professional; 30/35 hours/week</td>
<td>No significant difference in injury incidence.</td>
<td>The sample included dancers from a national ballet company.</td>
<td>Fair II</td>
</tr>
<tr>
<td>The injury panorama in a Finnish professional ballet company</td>
<td>Nissinen et al., 2001</td>
<td>Combined retrospective-prospective study</td>
<td>n = 98 (50 F, 48/50 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Professional; 30/35 hours/week</td>
<td>High incidence of lower back pain.</td>
<td>The study included dancers from a regional ballet company.</td>
<td>Fair II</td>
</tr>
<tr>
<td>Ballet dancers’ turnout and its relationship to self-reported injury</td>
<td>Copan 2002</td>
<td>Retrospective cohort study</td>
<td>n = 36 (27 F, 16/30 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Student, activity level</td>
<td>Turner was not significantly related to injury incidence.</td>
<td>The study included dancers from a major ballet company.</td>
<td>Fair II</td>
</tr>
<tr>
<td>Lumbar spinal pain in ballet school students: Pilot study</td>
<td>Dziewieksa et al., 2013</td>
<td>Combined retrospective-prospective study</td>
<td>n = 31 (16 F, 15/31 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Professional; 19/22 hours/week</td>
<td>No significant difference in pain levels.</td>
<td>The study included dancers from a ballet school.</td>
<td>Fair II</td>
</tr>
<tr>
<td>Traumatic injuries in professional dancers and present ballet injuries in Paris, 1984/85 and 2011/12</td>
<td>Warus et al., 2014</td>
<td>Retrospective cohort study</td>
<td>n = 25 (17 F, 8/25 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Professional, 19/22 hours/week</td>
<td>No significant difference in injury rates.</td>
<td>The study included dancers from a national ballet company.</td>
<td>Fair II</td>
</tr>
<tr>
<td>Kinematics of the lumbar spine during classical ballet postures</td>
<td>Faged et al., 2004</td>
<td>Retrospective-prospective study</td>
<td>n = 25 (17 F, 8/25 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Professional, 19/22 hours/week</td>
<td>No significant difference in movement patterns.</td>
<td>The study included dancers from a ballet company.</td>
<td>Fair II</td>
</tr>
<tr>
<td>The association between body build and injury occurrence in professional ballet dancers: expanded analysis for the injured body-locations</td>
<td>Zedzal et al., 2017</td>
<td>Retrospective-prospective study</td>
<td>n = 24 (24 F, 16/24 M) years</td>
<td>None specified</td>
<td>2</td>
<td>Professional, 19/22 hours/week</td>
<td>No significant difference in injury rates.</td>
<td>The study included dancers from a major ballet company.</td>
<td>Fair II</td>
</tr>
</tbody>
</table>

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### Appendix A. Summary of Articles examining Low Back Pain and Injury in Ballet Dancers (Continued)

<table>
<thead>
<tr>
<th>Article Title</th>
<th>First Author &amp; Year</th>
<th>Design</th>
<th>Collection Methods / Intervention</th>
<th>Level of Evidence</th>
<th>Sample size, mean age (range)</th>
<th>Terms Used</th>
<th>Level of Mastery &amp; Average Dance Participation</th>
<th>Relevant Outcomes: Males with LPB</th>
<th>Males with GP</th>
<th>Females with GP</th>
<th>Notes &amp; Limitations</th>
<th>Data Reported As</th>
<th>GRADE Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injuries in students of three different dance techniques.</td>
<td>Echagüen et al., 2019</td>
<td>Prospective cohort study</td>
<td>Medical records, sport physician recorded the data concerning injuries at least 6 months before the start of dance education Non-routine sampling convenience sample</td>
<td>2</td>
<td>n = 444 (77); 23.10 ± 3.64 years for modern; 23.05 ± 3.05 years for Spanish ballet; 21.05 ± 3.54 years for Spanish dance</td>
<td>back pain</td>
<td>Student, training 11.6–13.3 hours/week in 1.6 hours/week rehearsal</td>
<td>54/420, 4.70%; 1168 total injuries over 200 complete years of modern ballet</td>
<td>-</td>
<td>-</td>
<td>Cautioned about generalizability for the greater population since the goal of this study was feedback to the conservatory specifically.</td>
<td>Self-reported</td>
<td>Good II</td>
</tr>
<tr>
<td>Injuries in students of three different dance techniques.</td>
<td>Baker et al., 2010</td>
<td>Combined retro- and prospective study</td>
<td>Questionnaire: Medical records, questionnaire adapted Dance UK’s injury questionnaire and medical records from Injury Zone UK (Sport electronic athlete medical record system) Non-routine sampling convenience sample</td>
<td>3, 2</td>
<td>n = 57 (47 F); 20.0 ± 2.61 years for ballet; 21.5 ± 2.00 years for Spanish dance; 21.5 ± 2.00 years for Spanish ballet</td>
<td>lower back</td>
<td>Student, Self-Reported (32 hours/10-months, = 12 hours/month)</td>
<td>670/670, 6.6%; 21.4%</td>
<td>2/3</td>
<td>21.4%</td>
<td>Cautioned about generalizability for the greater population since the goal of this study was feedback to the conservatory specifically.</td>
<td>Self-reported</td>
<td>Good II</td>
</tr>
<tr>
<td>Self-reported and reported injury patterns in contemporary dance students.</td>
<td>Baker et al., 2010</td>
<td>Prospective cohort study</td>
<td>Questionnaire: Medical records, questionnaire adapted Dance UK’s injury questionnaire and medical records from Injury Zone UK (Sport electronic athlete medical record system) Non-routine sampling convenience sample</td>
<td>2</td>
<td>n = 174 (127 F); 26.15 ± 4.43 years average, 25.49 years</td>
<td>lower back injuries</td>
<td>Student, Reported (32 hours/10-months, = 12 hours/month)</td>
<td>670/670, 6.6%; 21.4%</td>
<td>2/3</td>
<td>21.4%</td>
<td>Cautioned about generalizability for the greater population since the goal of this study was feedback to the conservatory specifically.</td>
<td>Self-reported</td>
<td>Good II</td>
</tr>
<tr>
<td>Assessment of Compensated Tumour Characteristics and Relationship to Injuries in University Level Modern Dancers</td>
<td>Schiødt et al., 2015</td>
<td>Retrospective case-control study</td>
<td>Questionnaire: Self-reported injury of their own making Non-routine sampling convenience sample</td>
<td>3</td>
<td>n = 22 (20 F); 24.2 ± 1.37 years average</td>
<td>low back pain</td>
<td>Student, 20 hours/week plus time for various supplemental training</td>
<td>62/22, 27.3%</td>
<td>-</td>
<td>-</td>
<td>Concluded that all patients experienced tumour, but to a lesser degree than previous research.</td>
<td>People with each</td>
<td>Fair II</td>
</tr>
<tr>
<td>Injuries in Professional Modern Dancers: Incidence, Risk Factors, and Management</td>
<td>Shah et al., 2012</td>
<td>Retrospective case-control study</td>
<td>Questionnaire: Large scale survey, previous publication detailing the design (Weiss, 2003)</td>
<td>3</td>
<td>n = 184; 173 F; 18.55 years, 30.1 ± 3.53 years average</td>
<td>low back injury</td>
<td>Professional: 2.5 ± 1.5 hours/week in class, 17.2 ± 1.5 hours/week in rehearsal 6.3 ± 0.6 hours/week various supplemental training</td>
<td>40/30, 17%</td>
<td>-</td>
<td>-</td>
<td>Cautioned about generalizability for the greater population since the goal of this study was feedback to the conservatory specifically.</td>
<td>Self-reported</td>
<td>Good II</td>
</tr>
</tbody>
</table>

**Abbreviations used:**
- LPB: Low back pain
- LBP: Low back injury
- LBP/I: Low back pain or injury
## Appendix C. Summary of Articles examining Low Back Pain and Injury in Hip-Hop Dancers

<table>
<thead>
<tr>
<th>Article Title</th>
<th>First Author &amp; Year</th>
<th>Design</th>
<th>Collection Methods / Intervention</th>
<th>Level of Evidence</th>
<th>Sample size, mean age/Range</th>
<th>Terms used</th>
<th>Level of Maturity &amp; Average Dance Participation</th>
<th>Relevant Outcomes: Total number with LBP</th>
<th>Males with BP</th>
<th>Females with BP</th>
<th>Notes &amp; Limitations</th>
<th>Data Reported As</th>
<th>GRADE score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain Prevalence Among Female Street Dancers</td>
<td>GBG et al., 2017</td>
<td>Retrospective cross-sectional study</td>
<td>Questionnaires, used a basic health and data questionnaire and the SERF non-random sampling: volunteer sampling</td>
<td>3</td>
<td>n = 127 (97 F); 19.7 years average</td>
<td>&quot;lower back&quot;</td>
<td>Novice 3-5 hours/week 34/71: 45.6% 34/71: 46.6% Student 7-10 hours/week Professional 11-15 hours/week</td>
<td>19/34: 55.9% 19/34: 55.9% 9/16: 56.2%</td>
<td>9/16: 56.2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury Incidence in Hip-Hop Dancers</td>
<td>Oliwierski et al., 2019</td>
<td>Retrospective cross-sectional study</td>
<td>Questionnaire: A Web-based survey was conducted over a 6-month period attempted Random Sampling</td>
<td>3</td>
<td>n = 232 (110 F); range: 13, 64 years; F: 24.7 ± 5.5 years average; M: 23.4 ± 5.4 years average</td>
<td>&quot;Trunk, Lumbar/Pelvis, Injury&quot;</td>
<td>&quot;Student, Teacher, Professionals&quot; activity level not provided</td>
<td>Physical Complaint 0.1% (0%)</td>
<td>-</td>
<td>-</td>
<td>This study did not give the years of dancing but did not give current activity level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Musculoskeletal Injury in Break-dancers</td>
<td>Cho et al., 2009</td>
<td>Combined retro- and prospective case study</td>
<td>Questionnaire: Screenings, questionnaires was for the basic, and then they did routine radiographs for certain pieces, and then additional radiographs if a dancer had pain in an area that was not part of the routine. &quot;Diagnosis was based on findings from medical histories, physical examinations and radiologic examinations.&quot; No sampling, did not return mid-sampling technique at all</td>
<td>2</td>
<td>n = 42 (F): 22.3 years; M: 22.9 years; Range: 16-3 years</td>
<td>&quot;Number spine...Injury&quot;</td>
<td>Both (full tall): 10 hours of training per day, average: 4.1 hours</td>
<td>Both (full tall): 10 hours of training per day, average: 4.1 hours</td>
<td>20/106: 19.0% of the total group had LBP injury</td>
<td>21/42: 50.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations used:**
- LBP: low back pain
- LBI: low back injury
- LBP/I: low back pain or injury
ABSTRACT

Background: Sport-related concussion is a public concern with between 1.6 and 3.8 million sport- and recreation-related injuries occurring annually. An estimated 65% to 90% of concussed athletes show oculomotor disruption such as difficulty with saccades, accommodation, smooth pursuit, and fixation. A rapid number-naming saccade test, the King-Devick (K-D) test, has shown promising results as part of a multifaceted concussion assessment tool.

Purpose: The purpose of the current study was to evaluate the two versions of the K-D in collegiate aged (18-24) athletes to determine the agreement between versions. A secondary purpose was to investigate the association of K-D scores with sport, sex, use of glasses or contacts, and age of the athlete.

Study design: Descriptive laboratory study.

Methods: Division 1 NCAA collegiate athletes across ten sports were recruited to participate in baseline concussion assessments at the beginning of their respective athletic season. Correlations and multivariable logistic regression analyses were used to investigate the association of K-D scores with sex and age.

Results: One-hundred and nine athletes (69 males, 40 females; mean age = 20.40±1.38 years) were baseline tested. There was excellent agreement (ICC=0.93, 95% CI: 0.90, 0.95) between the paper and computer version. Preseason K-D scores were statistically different (r²=0.873, p<0.05) with athletes scoring a mean of 37.58 seconds on the paper version (95% CI, 36.21, 38.96) and athletes scoring a mean of 41.48 seconds for the computerized tablet version (95% CI, 40.17, 42.91). There were no significant differences in sex, sport, or use of glasses noted for both versions. Age differences were identified; eighteen-year-old athletes took statistically longer than their peers for both K-D versions. Pairwise comparisons showed statistically significant differences between 18-year olds up to the age of 21-year-olds (p<0.05) for the computer version and statistically significant differences between 18-year olds up to 22-year-olds (p<0.05) for the paper version.

Conclusion: This study supports the use of either version of the K-D test as a potential part of a multifaceted concussion assessment. The age of the athlete influences scores and therefore a K-D baseline should be repeated annually for collegiate athletes. Clinicians should not substitute K-D versions (computer vs. paper) in comparing baseline to a post-concussion K-D score as the scores are quite different.

Level of evidence: Level 3

Keywords: athletes; concussion; movement system; number-naming; oculomotor; saccades
INTRODUCTION
Concussion is a significant public health concern, prompting researchers and healthcare providers to investigate tools for assessment. In sport-related concussions, healthcare providers must decide on assessment tools that are efficient, affordable, and evidence-based. Baseline concussion testing of an athletic team using the recommended multifaceted approach can take hours. Therefore, healthcare providers face a conundrum when considering what tools to use, and must consider the time and effort of testing that is evidence-based. For example, in a rural high school or collegiate setting, there may only be one athletic trainer to baseline test 50 to 500 athletes. The school may not be able to meet all recommended guidelines for testing due to financial and personnel resource constraints. This leaves the athletic trainer facing the dilemma of deciding on what he or she can reasonably use for assessment tools from both a logistic and economic approach.

A multifaceted approach to baseline concussion assessment is recommended and should evaluate as many neuroanatomical functions efficiently as possible. Oculomotor assessment of saccades is supported in the literature as one component of a multifaceted evaluation of an athlete suspected of having a concussion. The King-Devick (K-D) test has been well researched and authors have reported excellent test-retest reliability in athletes from multiple sports. These cohorts were predominantly male with smaller sample sizes. In 2015, King-Devick Technologies, inc phased out the original spiral-bound, or paper, version to a computerized tablet version. Differences in the two versions have been examined in younger athletes (mean age of 15.7) and excellent agreement (ICC = 0.92, 95% CI 0.82, 0.96) was found. Recently, researchers examined the two versions of the K-D in collegiate athletes and found similar results as the previous study investigating younger athletes.

The computerized tablet version of the K-D requires an electronic device for collecting data and requires an annual subscription whereas the paper version of the K-D is inexpensive. The manufacturer of the K-D suggests that the computerized tablet version K-D is more effective in assessing oculomotor function as compared to the paper version. The purpose of the current study was to evaluate the two versions of the K-D in collegiate aged (18-24) athletes to determine the agreement between versions. A secondary purpose was to investigate the association of K-D scores with sport, sex, use of glasses or contacts, and age of the athlete. The hypothesis was that the paper K-D test would positively correlate with the computer version K-D test.

METHODS
The current study used a prospective cohort research design to evaluate the King–Devick test trials in 109 Division 1 NCAA collegiate athletes. For inclusion in the study, athletes were required to be 18 to 24 years old and possess sufficient English language skills to complete all tasks. Exclusion criteria were lower extremity musculoskeletal injuries in the prior three months; a history of a head injury in the past year; or a diagnosis of visual, vestibular, or balance disorders. Additionally, athletes were asked if they had ever been diagnosed as having a learning disorder, attention deficit disorder, or dyslexia, and athletes were excluded if the answer was affirmative. Athletes provided informed consent and all experimental procedures were approved by the institutional review board at Northern Arizona University. Athletes were recruited between July and December 2017. All testing was conducted within the university athletic training room to provide adequate lighting. Background noise and distractions were not controlled and varied across baseline testing days. Athletes were permitted to use glasses or contacts if they were needed to perform the test. The K-D test was performed with the athlete in a seated position at a self-selected distance for reading both versions of the K-D, which was approximately 40 cm away from the athlete, similar to recent studies. All athletes received standardized instructions before performing both versions of the K-D test in random order. The researcher, when testing with the paper version, started the stopwatch timer for the K-D score when the athlete read the first number on the K-D, and stopped the timer when the participant completed the last number of the K-D test card. The computerized tablet version timer started or stopped by the researcher touching the screen in between each K-D test card. This procedure was repeated two times and randomized by a random number
generator for both versions of the K-D test and the K-D baseline score was recorded for both versions of the test. If the athlete made an error, the K-D test card was repeated until error-free.

A power analysis was conducted using PASS software version 12 (NCSS Statistical Software, Kaysville, Utah) that indicated that 82 participants were needed. For the current study, ICC’s were used to measure agreement, and an ICC less than 0.40 indicated poor reliability, an ICC between 0.40 and 0.75 indicated moderate to good reliability, and an ICC greater than 0.75 indicated excellent reliability.18 Significance was set at (p<0.05) and 95% confidence intervals were reported when appropriate. Statistical software program SPSS version 24.0 (IBM, Armonk, New York) was used for the analyses.

RESULTS

One hundred and nine athletes (69 males, 40 females; mean age = 20.40 ± 1.38 years) were baseline tested. The demographic characteristics of the athletes, as well as the K-D score, are shown in Table 1. Pre-season K-D scores were correlated across version but statistically different (r = 0.873, p < 0.05) with athletes scoring a mean of 37.58 seconds on the paper version (95% CI, 36.21, 38.96) and athletes scoring a mean of 41.48 seconds for the computerized tablet version (95% CI, 40.17, 42.91) (Table 1). Figure 1 shows the regression model comparison of the paper version to the computerized tablet version of the K-D (p < 0.05, R² = 0.762). As can be observed in Figure 1, all K-D results were included and two athletes had prolonged scores on both versions of the K-D.

The mean K-D score comparisons for both versions of the K-D specific to the athlete’s sport participation are presented in Table 2. The mean K-D score comparisons specific to sex are presented in Table 3. The mean K-D score comparisons specific to the use of glasses or contacts are presented in Table 4. There were no significant differences noted for both K-D versions scores by sex, sport, or use of glasses. Table 5 shows the mean K-D score comparisons specific to age. Age differences in scores were identified across ages, but the eighteen-year-old athletes took longer than their peers for both versions of the K-D. Pairwise comparisons showed statistically significant differences between 18-year-olds up to the age of 21-year-olds (p < 0.05) for the computer version and statistically significant differences between 18-year-olds up to 22-year-olds (p < 0.05) for the paper version.

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* K-D=King-Devick; K-D computer score, K-D paper score, and age are reported as mean (SD).
DISCUSSION
These findings support that either the paper or the computerized version of the K-D test can be used as a baseline concussion measure for collegiate athletes. Reliability of the K-D test has been examined in multiple sports to include boxing, mixed martial arts, basketball, hockey, soccer, football, volleyball, rugby, softball, cheerleading, as well as in Army soldiers and recreational athletes. Intraclass Correlation Coefficients (ICC) ranged from 0.81 to 0.98 indicating excellent test-retest reliability. ICC’s are used as a marker of repeatability in measures that are continuous and the findings of these studies are indicative of the ability of the K-D to repeatedly measure performance on a saccadic number-naming test across sport. In terms of an evidence-based concussion assessment tool, the K-D appears to be reliable in multiple sport populations.

In a recent study investigating collegiate athletes, authors investigated differences between the paper and computer version of the K-D during baseline testing. The authors investigated 13 women’s and 11 men’s collegiate sports and reported baseline K-D means of 42.8 seconds (95% CI, 42.1-43.3) and 40.0 seconds (95% CI, 39.7 to 40.3) for the computer and paper respectively. The authors noted a 2.8-second difference in the two versions of the K-D in athletes in their first year of collegiate athletic participation. The authors excluded athletes with a diagnosis of a learning disorder or attention deficit hyperactivity disorder. In the current study athletes differed

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by 3.9 seconds between the two versions of the K-D which is similar to the 3.7-second difference noted by Raynowska et al. The current study found similar time differences to other authors' findings with the computer version being slower than the paper version of the K-D. This finding reinforces the Clugston et al. findings that K-D scores are slower on the computer version and that the two versions of the K-D should not be used interchangeably as it may lead to the potential of underdiagnosing or overdiagnosing concussion.

The authors of the current study examined the two available administration versions of the test and found that their scores are highly correlated which suggests that the test is measuring the same construct. However, the scores are likely to differ (computerized version slower), thus, the authors would like to suggest that clinicians should not use one version of the K-D such as the paper version at baseline and another version such as the computer version after a suspected concussion as there is a statistically significant difference in the measures obtained between the two versions of this test. Two independent studies found similar results when comparing the two versions of the K-D but did not report the effect of confounding variables such as sex, sport, use of glasses/contacts, or age. The current study did not reveal significant differences for sex, sport, or use of glasses/contacts but significant differences were present when the age of the athlete was considered.

Similar to the findings of other authors investigating the K-D, the current study findings suggest that the age of the athlete should be considered when interpreting the K-D test. In terms of comparing age groups of athletes, several authors have noted age differences with improved K-D scores as age increases in junior high school, high school, college, and in professional athletes. Weise et al. performed a cross-sectional study of junior high and high school athletes (mean age of 14.2) to compare relationships of the K-D to Optometric tests (ocular alignment, near point convergence, and pupil function via pupillometry). Weise et al. reported no association between K-D and near point of convergence, ocular alignment, or pupillometry which suggests that these measures are evaluating different aspects of vision. The researchers did note that K-D scores improved, or decreased in time, with increasing age in junior high and high school athletes up to the age of 18 as they did not investigate older athletes. Hasanaj et al. compared collegiate hockey athlete K-D scores to consider age differences in a small sample size (n=13). Hasanaj et al. reported older age was a predictor of increased time, or poor K-D scores occurred for K-D baseline scores in older healthy males. The authors concluded that athlete age at the time of baseline testing should be considered when interpreting K-D scores and that increasing age may be a marker for the duration of contact sports exposure. Galetta et al. have noted that athletes that took 5.9 seconds longer to complete the K-D in comparison to baseline scores were indicative of a concussion. Therefore, it is important to make sure that K-D testing is precise to ensure that athletes are not being misdiagnosed as having a concussion.

In the current study, the results suggest age differences in collegiate athletes need to be considered. Similar to other studies of collegiate athletes, almost all of the athletes in the current study improved their...
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| Based on estimated marginal means

* The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
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Health care providers must use evidence-based tools. Recent studies have investigated the use of the K-D in comparison to other evidence-based concussion assessment tools to determine if the K-D is measuring a similar or different construct. The Vestibular Ocular Motor Screening (VOMS) is an evidence-based tool that has been investigated and is free. There are seven assessment components in the VOMS: saccades for horizontal and vertical, vestibular ocular reflex for horizontal and vertical, visual motion sensitivity, smooth pursuit, and near point convergence. Recently, authors investigating the use of the VOMS found that all seven assessment components of the VOMS were strongly correlated with K-D scores in concussed adolescents.27 Specifically, two of the seven assessment components (near point convergence and visual motion sensitivity) predicted K-D scores.27 Although the two assessment components of the VOMS are both visual tests and the K-D is an oculomotor test, the visual system is quite complex and these three tests involve different anatomical components of vision that change the angle of visual focus or gaze.4 The assessment components of these three vision tests utilizes different anatomical components of vision specifically saccades, vergence, and smooth pursuit. The VOMS and the K-D evaluate these three components of vision and only recently do authors suggest to collect this information at baseline as a reference comparator. The authors of the current study stress the importance of using an objective standardized approach to ensure reliable tests that assess as many neuroanatomical locations as possible in an efficient manner.

Limitations of the current study include a sample of convenience as athletes were recruited from the local university athletic department. Another potential limitation is that athletes were tested in a busy athletic training department which does not allow optimal circumstances of testing in a controlled quiet laboratory which could have influenced attention during testing of the athletes but best replicates clinical settings. Background noise and distractions were not controlled throughout the study and varied across baseline testing days. The authors note that this is a limitation that did vary across testing days but is realistic to a busy athletic training department. Another limitation was that representation across sports was not evenly distributed as it was reflective of the number of athletes within the sport. Ideally,
when investigating differences across sports, there should be an even distribution across the sport to compare for differences.

CONCLUSION
This study supports the use of either version of the K-D test as a potential part of a multifaceted concussion assessment. The results of the current study suggest that the age of the collegiate athlete influences K-D scores therefore clinicians should consider testing athletes on an annual basis. Secondary to the differences noted in baseline scores across the two versions of the test, clinicians should not substitute K-D versions (computer vs. paper) in comparing baseline to a post-concussion K-D score. The authors recommend that clinicians perform a K-D test at baseline and that the K-D could be repeated annually for collegiate athletes.

REFERENCES


ABSTRACT

**Background:** Analysis of upper extremity weight bearing ability is important for athletes as some function largely in a closed chain capacity (e.g., wrestling, football, gymnastics); also, all require closed chain upper extremity function during strength and conditioning. Additionally, in a rehabilitation setting, closed chain upper extremity functional testing is often used as a return to play criterion. Lower extremity sway measures (biomechanical and clinical) have been published widely and have established reliability and validity; however, the reliability of upper extremity sway biomechanical measures has not been investigated to date.

**Hypothesis/Purpose:** The purpose of this study was to determine the repeatability of a variety of force plate measurements during an upper extremity task in an athletic population. It was hypothesized that variables measuring upper extremity sway in a closed kinetic chain position would have excellent reliability.

**Study Design:** Cross-sectional.

**Methods:** All data were collected using a force plate system with commercially available software. Four hundred and ninety healthy Division I athletes were tested for both their dominant and non-dominant upper extremity at one of two testing sessions. Subjects were instructed to stay as still as possible while maintaining a full plank position with one upper extremity on the force plate and the contralateral upper extremity behind their back. Two, 20-second trials were performed for each extremity. Variables measured included average sway velocity (ASV), sway velocity in medial-lateral (SVML) and anterior-posterior (SVAP) directions, sway velocity at 1st and 2nd time intervals for AP (VAP1 and 2) and ML (VML1 and 2) directions, and sway frequency in the AP direction for 1st and 2nd time intervals (FreAP1 and 2). Intraclass correlation coefficients (ICC(2,1)) and their 95% confident intervals were calculated for all force plate variables for 980 limbs.

**Results:** No difference was seen between left and right extremities for any measure (p > 0.05). ICC's ranged from 0.61-0.90 for all variables, indicating moderate to excellent reliability for all variables.

**Conclusion:** Upper extremity sway biomechanical variables using a force plate system have moderate to excellent reliability. These results are important prior to validation and clinical utilization of these measures including baseline testing, return to play guidelines, and injury prevention parameters.

**Level of Evidence:** 3.

**Keywords:** biomechanical testing; movement system; reliability, upper extremity
INTRODUCTION

Biomechanical analysis of lower extremity postural sway variables has been found to be reliable and valid to quantify balance performance for both healthy individuals and individuals with an injury.1-3 Upper and lower extremity postural control is controlled by integrated information from the visual, somatosensory, and vestibular systems. The integrity of the postural control system is typically evaluated with static or dynamic posturography. Postural steadiness, or static posturography, characterizes the performance of the postural control systems in a static position. In the lower extremity, this is often evaluated in both eyes open and eyes closed trials to estimate the role of the visual system while maintaining balance. This postural steadiness or sway is quantified biomechanically by the displacement of the center of pressure on a force platform. These variables can further be quantified into displacement variables, such as mean deviation from center of pressure or path length, or other variables which express the magnitude that the center of pressure moves during a trial. Additionally, velocity-based variables can be utilized to express how quickly the center of pressure is moving during a trial, indicating how quickly this subject is adjusting to maintain their balance. The center of pressure variables reflect the orientation of the body segments as well as the movements of the body to keep the center of gravity over the base of support.2,4 Correspondingly, these measures can be used to assess upper extremity stability and proprioception, quantified by variables measuring the ability of the upper extremity to remain still in a weightbearing position.4,5

Despite extensive work utilizing sway data in the lower extremity,1-4 there is a paucity of literature describing its use for upper extremity testing. In 2007, Pontillo and colleagues investigated the demands of upper extremity weight-bearing exercises on shoulder musculature by electromyographic analysis.5 The authors found that triceps, serratus anterior, and anterior deltoid muscles activity significantly increased as each trial progressed, irrespective of stability condition, indicating that fatigue should be considered when using this position for the assessment of stability. Closed kinetic chain (CKC) upper extremity assessment is necessary for several reasons. First, certain diagnoses occur most often in closed chain positions, such as posterior glenohumeral instability and posterior labral tears; elbow dislocations; triangular fibrocartilage complex tears, and ulnar impaction syndrome.6,7 Additionally, certain sports require athletes to function largely in a closed chain position(s), such as football, gymnastics, and wrestling. However, even in the absence of sport-specific CKC skills, most athletes require CKC function for strength and conditioning activities (e.g., planks, push-ups). Thus, assessment of upper extremity function is necessary to mimic sport-specific demands. Upper extremity CKC positions test several facets of function simultaneously; the positions require co-contraction of the upper quarter musculature, the ability to withstand both shear and compressive forces, and core stability.8 These systems must work in a synchronized manner to stabilize the upper extremity; ergo, postural stability measures in upper extremity weight bearing can be used to assess these facets.

Several clinical assessments require CKC function of the upper extremity, including the closed kinetic chain upper extremity stability test,8,10 the upper quarter Y-Balance Test,11-12 and the two-minute timed push-up test.13 At this time, there is a paucity of literature investigating biomechanical measures of CKC upper extremity function. Recently, Gillen and colleagues14 found that plyometric push-ups off a force plate were a reliable measure of strength and peak rate of force development (both demonstrated ICC’s > 0.8).

There have been no large-scale studies which examine the repeatability for force plate variables for the upper extremity. Therefore, the purpose of this study was to determine the repeatability of a variety of force plate measurements during an upper extremity task in an athletic population. It was hypothesized that both the amplitude and direction variables would have good to excellent reliability, as these have been determined for similar lower extremity studies.1-3

METHODS

Approval was obtained from University of Pennsylvania Health System’s institutional review board. All data were collected using a force plate (Kistler Inc; Amherst, NY, USA) system connected to a dedicated
The athlete was instructed to maintain their balance with as little movement as possible. They are instructed to start in a standard push up position, then when prompted, they place their contralateral arm either across their chest or behind their back. They were instructed to perform the task naturally so that they could complete the test. Should an error (shifting the weight from the weightbearing upper extremity, or touching down the opposite upper extremity) occur, the system would register this as an error and terminate the test. The trials with error(s) were repeated until a valid trial was obtained. Two, 20 second trials were performed for each extremity, alternating limbs, with a 15-second break between trials. Trial time was determined by the options the initial software provided as well as initial reliability testing that showed that 20 seconds was adequate time to capture fatigue changes, without being over taxing on the body. It also makes the test more accessible to people, as these tests are done prior to usual strength and conditioning. This also is consistent with other biomechanical UE testing in weightbearing. The subjects were blindfolded during testing to eliminate the visual component of balance. The force plate filtered and smoothed the resultant output. Center of pressure data was quantified by velocity and frequency of motion. The Sparta Science software labelled and processed the data into the appropriate variables. Operational definitions of variables measured are presented in Table 1 (below).

### Statistical Methods

Independent samples T-tests were used to determine if differences existed between sides (left versus right). If no difference between sides existed, data would be averaged across the two trials by side (left, right). Intraclass correlation coefficients (ICC

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**Table 1.** All variables, variable definitions, ICC(2,1) values, 95% confidence intervals of ICC(2,1) values, standard error of measure (SEM), and minimal detectable change (MDC) values.

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<th>ICC(2,1)</th>
<th>95% CI</th>
<th>SEM</th>
<th>MDC (95% CI)</th>
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<td>ASV average sway velocity</td>
<td>0.700</td>
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<td>SVAP sway velocity in anterior-posterior (AP) direction</td>
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<td>SVML sway velocity in mediolateral (ML) direction</td>
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<td>0.008</td>
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<td>0.858-0.890</td>
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and their 95% confident intervals were calculated using SPSS statistical package version 25 (SPSS Inc, Chicago, IL) based on a mean-rating ($k = 2$), absolute-agreement, one-way mixed-effects model, for all force plate variables for 980 limbs. Standard error of measure and minimal detectable change (95% CI) were also calculated.

RESULTS
No differences were seen between left and right extremities for any of the measures ($p < 0.05$). ICC$_{(2,1)}$ values ranged from 0.61-0.90 for all variables, indicating moderate to excellent reliability for all variables. Additionally, Table 1 provides standard error of measurements and minimal detectable change values for each variable.

DISCUSSION
This is the first study to examine the reliability of a unilateral closed chain upper extremity task using force plate measures. Moderate to excellent reliability was found for all the variables assessed. In addition to average sway velocity, sway velocity was also examined in both medial-lateral and anterior-posterior directions. Typically, force plate measures of postural steadiness are either related to the magnitude or velocity of the motion. Sway velocity indicates the speed at which the center of pressure moves, indicating the subjects' ability to stabilize their upper extremity during the task. It is common to examine these variables in both the medial-lateral and anterior-posterior directions, as these are likely to be influenced by different muscle groups. Additionally, the sway velocity and frequency were examined during early and later intervals for the task; it is important to look at velocity during time intervals, as stability is usually more challenging as time increases, and these had moderate to high ICC$_{(2,1)}$ values, indicating that the total task time was appropriate and not affected by fatigue. This also indicates that the length of the trial was appropriate, as the second time interval showed decreased reliability; a longer task may have decreased the reliability even more.

Lower extremity sway or postural stability measures have been investigated extensively, and show large variability, with anywhere from poor to excellent reliability. The reported reliability values in this study are all moderate to high, indicating that this task can be easily replicated. Additionally, as it is known that there is a visual contribution to postural stability, measurements obtained in an eyes closed condition are often lower than the eyes open condition.

Upper extremity closed chain functional testing is important for several reasons. First, the position assesses several facets of function simultaneously (ability to withstand sheer and compressive forces through all upper extremity joints, co-contraction of upper quarter musculature; and core stability). The CKCUEST is performed by starting the athlete in a full plank position, which is similar to the position utilized in this study, and correlates with isometric rotator cuff strength for elevation ($r = 0.7$), external rotation (ER) ($r = 0.7$) and internal rotation (IR) ($r = 0.8$); peak isokinetic ER/IR strength ($r = 0.9$); grip strength ($r = 0.8$); isolated neuromuscular control of core ($r = 0.4$). Uhl et al (2003) compared the one-arm push up position to other closed chain upper extremity positions, and found that it requires 60% of the subjects' body weight in force to maintain the position; thus, it is known that to maintain this test position, each extremity must be able to withstand compressive forces at the wrist, elbow, and shoulder joints. Also, upper extremity weight bearing positions elicit extremely high deltoid and infraspinatus activity, with fair to moderate muscle activity in the supraspinatus and pectoralis major as well. This position also mimics some sports specific tasks (e.g.: blocking in football, all handstand/hand-spring skills in gymnastics) well as strength and conditioning demands (e.g., push-ups, planks, etc).

The results of this study have clinical implications. As these biomechanical measures have good to excellent reliability in normal subjects, they could be utilized to compare upper extremity closed chain function between the extremities. The sample showed no difference between extremities for any variable, thus limb symmetry should be expected in healthy athletes across all sports, and asymmetry in such measures could indicate an area for concern.

As athletes who participated in open chain, unilaterally dominant sports were included in the study, the
absence of asymmetry finding was somewhat surprising. This can be attributed to the fact that although it is a closed chain upper extremity task, successful task completion requires core stability, and perhaps this could be considered an assessment of both upper extremity stability and core stability simultaneously.

Future directions should include validation of these measures against clinical measures of upper extremity function and/or core stability. This would be useful for incorporation of this task into upper extremity and/or trunk return to play protocols. Additionally, the same measures could be studied in populations that include injured athletes.

CONCLUSION
The results of the current study indicate that upper extremity sway biomechanical variables using a force plate system have moderate to excellent reliability. These results are important prior to validation and clinical utilization of these measures including for baseline testing, return to play guidelines, and use in injury prevention.

REFERENCES
ABSTRACT

Background: Rehabilitation following shoulder surgery involves the use of resistive exercise but dosing of these exercises historically employs multiple sets of pre-determined repetitions and few reports document the perceived effort encountered by patients during these exercises for both elastic resistance and free-weights. The OMNI-Resistance Exercise Scale (OMNI-RES) has been tested and applied as a measure of perceived exertion (RPE) for resistive exercise but has not gained widespread acceptance as an optimal method for physical therapists to document RPE during rehabilitation of shoulder surgery.

Purpose: To generate descriptive values of RPE encountered during common shoulder exercises of varying resistance in patients following shoulder surgery as well as provide a comparative analysis between perceived exertion ratings of similar exercise movement patterns using elastic and traditional isotonic resistance.

Study Design: Descriptive Cross-sectional Cohort

Methods: Sixty-six subjects (mean age 53.3 ± 12.8 years) were included in this study following shoulder surgery (RC repair n = 22, labral repair n = 10, SA n = 34). Perceived exertion using the OMNI-RES was recorded during performance of seven rotator cuff and scapular rehabilitation exercises at 6- and 12-weeks following surgery.

Results: Mean RPE using OMNI-RES in combined surgical groups ranged between 3.6 and 5.7 (mean = 4.5 ± 2.1) across all seven exercises (scale 0 = very easy to 10 = extremely hard). From the external rotation (ER) exercise pair, paired t-tests revealed standing ER w/ Thera-band® (ERB) had a significantly higher OMNI-RES score versus sidelying ER w/ cuff weight (SLERW) (mean: 5.13 vs 4.41, p = 0.001) while the extension exercise pair consisting of standing shoulder extension w/ band (EXTB) and prone extension w/ cuff weight (PEXTW) showed no significant difference in OMNI-RES score (mean: 3.54, 3.67, p = 0.626).

Conclusion: Commonly prescribed resistance exercise in the rehabilitation following shoulder surgery show light-moderate ratings of perceived exertion at both 6 & 12 week post-operative timepoints across three surgical procedures.

Level of Evidence: 3b

Keywords: OMNI-RES, rating of perceived exertion, resistive exercise, shoulder, movement system
INTRODUCTION
Musculoskeletal disorders of the shoulder complex are common reasons to seek both non-operative and surgical medical care. It is estimated that over 270,000 rotator cuff (RC) repairs were performed in the United States in 2006 and the incidence of RC repair is rising.\textsuperscript{1,2} Also, anterior shoulder instability is common,\textsuperscript{3} and patient outcomes may be improved following surgical stabilization via labral repair versus non-operative management.\textsuperscript{4,5} Additionally, shoulder arthroplasty (SA) is being increasingly selected in recent decades for patients with shoulder osteoarthritis.\textsuperscript{6} Following surgery, therapists use varying post-operative protocols to manage symptoms, restore range of motion, and improve shoulder and scapular muscle strength and endurance.\textsuperscript{7–10} While rotator cuff strength has been shown to gradually improve within the first post-operative year,\textsuperscript{11} there are no widespread, clinically accepted dosage parameters for resistive exercise. Given potentially high RC re-tear rates following repair,\textsuperscript{12} recent literature has focused on the timing of exercise introduction in efforts to maximize clinical outcomes.\textsuperscript{13,14} There has been little focus on the optimal dosing of resistive exercises and programs are often standardized to a specific exercise volume with variable consideration of patient subjective report and exercise intensity. A review of therapeutic exercise for rotator cuff tendinopathy concluded that pain and/or fatigue can be used to successfully guide rehabilitation programs but specific recommendations for acceptable levels of fatigue were not reported as only two of the fourteen articles reviewed mentioned fatigue levels as a guide for exercise.\textsuperscript{15} Rating of perceived exertion (RPE) scales are widely used as a way of monitoring and tracking exercise intensity. Previous literature has suggested a positive linear relationship between exercise intensity levels and ratings of perceived exertion during bouts of resistive training.\textsuperscript{16–20} The OMNI-Resistance exercise scale (OMNI-RES) has been developed to monitor RPE of both the overall body experience and active muscle groups for resistive exercise.\textsuperscript{17} The OMNI-RES is a 0-10 scale for use among males and females of all ages as a tool to control intensity of strength training. The OMNI-RES scale differs from other RPE scales, such as the Borg CR10 scale,\textsuperscript{21} by offering a resistance exercise-mode specific pictorial\textsuperscript{17} to assist participants rate tasks accurately. In a study to establish the instrument’s concurrent validation, Robertson et al\textsuperscript{17} monitored total weight lifted, blood lactic acid concentration, and rating of perceived exertion for active muscles (RPE-AM) and overall body (RPE-O) using the OMNI-RES during weight-lifting against the force of gravity.

Thera-band\textsuperscript{®} (TB) resistance bands and tubing are commonly used in various postoperative shoulder rehabilitation protocols.\textsuperscript{22,23} Colado et al\textsuperscript{24} examined the construct and concurrent validity of the OMNI-RES scale for TB resisted shoulder lateral and frontal raise exercises (OMNI-RES EB). A new OMNI-RES diagram for use with elastic band exercises was developed which exchanged images of elastic bands with the weighted barbells seen on the original diagram. Correlations between RPE from the OMNI-RES EB and the TB RPE scale using regression analysis established construct validity reporting significant differences (p ≤ 0.05) in electromyography (EMG) activity, heart rate, and RPE scores between the high and low intensity sets of two separate exercises. Overall and active muscle RPE scale scores demonstrated intraclass correlation coefficient values of 0.67 and 0.58 respectively. Validity coefficients ranged from $r^2=0.76$ to 0.85 for PRE-AM and $r^2=0.87$ for RPE-O.

Based on the validation results, the OMNI-RES can be used to monitor exercise intensity using both isotonic weights and elastic resistance. For this study, the OMNI-RES was used postoperatively to track and generate descriptive RPE during seven commonly utilized exercises involving both free weights and TB elastic bands at 6 and 12 week postoperative time points. The purpose of the study was to generate descriptive values of RPE encountered during common shoulder exercises of varying resistance in patients following shoulder surgery as well as provide a comparative analysis between perceived exertion ratings of similar exercise movement patterns using elastic and traditional isotonic resistance.

METHODS
Patients between the ages of 18 and 75 undergoing rehabilitation following RC and labral repair and SA were asked to volunteer to participate in this study. All post-surgical patients during the study period were given the opportunity to participate in the
Patients were tested during their 6th and 12th post-operative weeks following RC and labral repair or SA. No minimal range of motion or strength requirements were required for inclusion in this study. Prior to involvement, all subjects signed an informed consent. This cross-sectional cohort study was reviewed and approved by the IRB of Physical Therapy Associates (Exton, PA). Standardized data collection forms were used to guide consistent acquisition of data from the patient during a designated rehabilitation session ± 1 week from the 6th and 12th post-operative week of rehabilitation. All rehabilitation and data collection was performed at a single clinic, with patients from the lead author's caseload.

With the OMNI-RES placed in front of them in clear view, patients were asked, “How hard do you feel your muscles are working?” to estimate their overall muscular effort level after a series of designated exercises during one specific rehabilitation session in the 6th and 12th week following surgery. Exercises chosen for this research have been previously studied with EMG and are known to create moderate to high levels of activation of the rotator cuff and scapular musculature. During these data acquisition sessions, exercises were performed in a randomized fashion using a random numerical generator to minimize the effects and possibility of a systematic bias from muscular fatigue in this investigation. Due to the advanced nature of certain exercises selected for this study, not all exercises were completed by all patients. Each participant’s exercise routine was decided based on surgical procedure, post-operative time point, age, muscle strength, and functional goals. If appropriate, patients performed both exercises within an exercise pair. Table 1 lists the exercises studied in this investigation and the time point during which the subject was asked to rate the perceived exertion using the OMNI-RES. Repetition-based and time-based exercise were performed for two sets of fifteen repetitions and two sets of 30 seconds, respectively, during both standard follow-up visits and data collection sessions. The patient was asked to provide RPE immediately following completion of the exercise.

Patients were tested at two time points during their rehabilitation following surgery using identical procedures during each data collection session.

<table>
<thead>
<tr>
<th>Table 1. Rehabilitation Exercises and Timing of OMNI-RES Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sidelying external rotation with cuff weight (SLERW), weight applied at the wrist. After 2nd set of 15 repetitions.</td>
</tr>
<tr>
<td>2. External rotation oscillation at 100% elongation with elastic resistance (EROB) with Thera-band® tubing. After 2nd set of 30 seconds.</td>
</tr>
<tr>
<td>3. External rotation with retraction with elastic resistance (ERRB) at 100% elongation with Thera-band® tubing. After 2nd set of 15 repetitions.</td>
</tr>
<tr>
<td>4. Prone extension with external humeral rotation with cuff weight (PEXTW), weight applied at the wrist. After 2nd set of 15 repetitions.</td>
</tr>
<tr>
<td>5. Prone horizontal abduction with external humeral rotation with cuff weight (PHABW), weight applied at the wrist. After 2nd set of 15 repetitions.</td>
</tr>
<tr>
<td>6. Standing external rotation with elastic resistance (ERB) at 100% elongation loading with Thera-band®. After 2nd set of 15 repetitions.</td>
</tr>
<tr>
<td>7. Standing extension with scapular retraction with elastic resistance (EXTB) at 100% elongation with Thera-band® tubing. After 2nd set of 15 repetitions.</td>
</tr>
</tbody>
</table>

Collection was performed by one of two Physical Therapists or one Certified Athletic Trainer using common verbiage and procedures as outlined. The resistance level (cuff weight) and TB color used during each exercise was recorded by the examiner. Resistance levels for each exercise were selected using the resistance level that allowed the patient to perform the exercise without pain, and to perform the movement without compensation during all repetitions. The patient used the resistance levels from their prior session of rehabilitation during the testing sessions. To standardize resistance levels of the resistance bands during the testing procedure, markings on the floor were used to represent 100% elongation of the band. For shoulder extension, 100% elongation corresponded to the position of 45 degrees as pictured which was mid-way through the movement performed by the subject (Figure 1a). For external rotation, 100% elongation corresponded to the position of 45 degrees of internal rotation again approximately mid-way through the exercise range of motion (Figure 1b). This resulted in the desired band tension forces reported in Table 2.

STATISTICAL METHODS
All data were entered into an Excel Spreadsheet and analyzed using SPSS (Chicago, IL). Descriptive statistics were generated and analyzed with comparison between select means performed for paired exercises (elastic resistance vs traditional isotonic cuff weight) using a paired t-test.

RESULTS
Sixty-six subjects participated in this study. Subjects mean age was 53.3 ± 12.8 years. Ten subjects were
status-post labral repair, 22 had arthroscopic RC repair, and 34 were status-post anatomic SA.

Table 3 presents the mean OMNI-RES ratings from the seven exercises of 4.5±0.79 (Range 3.6-5.7) across all surgical groups at 6- and 12-week post-operative time-points. Among this cohort, external rotation oscillation with TB (EROB) and standing extension with TB (EXTB) had the highest and lowest perceived exertion scores, respectively (OMNI RES: 5.7, 3.6). Across all surgical groups, OMNI-RES averages were similar in the 6-week and 12-week post-operative sub-groups (4.2 versus 4.6) with the average absolute mean difference (AMD) between individual exercises at 6 versus 12 weeks post-op found to be 0.5 (Table 4).

Table 5 shows statistical results of comparisons between OMNI-RES ratings for common exercise pairings (external rotation: sidelying with cuff weight (SLERW), standing with elastic resistance (ST) and oscillation using TheraBand Flexbar, Performance Health, Akron, OH, USA).
(ERB); shoulder extension: prone extension with cuff weight (PEXTW), standing shoulder extension with elastic resistance (EXTB)). The shoulder external rotation exercise pair using either a cuff weight or TB (SLERW, ERB) was found to have significantly higher perceived exertion during ERB than SLERW (p = 0.001) while the shoulder extension exercise pair (PEXTW, EXTB) revealed no difference in perceived exertion (p = 0.626). Additionally, Table 6 shows the comparison between paired exercises (external rotation and extension) displaying the frequency of resistance band intensity with the most frequently used cuff weight resistance levels. With reference to the SLERW and PEXTW exercises, patients most often used yellow TB during ERB and EXTB (82, 74% respectively) when recorded to use

<table>
<thead>
<tr>
<th>Exercise</th>
<th>6 Weeks</th>
<th>12 Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean</td>
</tr>
<tr>
<td>1. SLERW</td>
<td>33</td>
<td>4.4</td>
</tr>
<tr>
<td>2. EROB</td>
<td>13</td>
<td>5.2</td>
</tr>
<tr>
<td>3. ERRB</td>
<td>10</td>
<td>3.5</td>
</tr>
<tr>
<td>4. PEXTW</td>
<td>23</td>
<td>3.7</td>
</tr>
<tr>
<td>5. PHABW</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>6. ERB</td>
<td>31</td>
<td>4.8</td>
</tr>
<tr>
<td>7. EXTB</td>
<td>31</td>
<td>3.3</td>
</tr>
<tr>
<td>Average</td>
<td>21</td>
<td>4.2</td>
</tr>
</tbody>
</table>

N=Combined surgical groups of participants performing exercise at 6 and 12 weeks post-op
Abbreviations: AMD = Absolute Mean Difference (6 week mean – 12 week mean), Std. Dev. = standard deviation, SLERW = sidelying ER w/ cuff weight, EROB = external rotation oscillation w/ band, ERRB = external rotation and retraction w/ band, PEXTW = prone extension w/ cuff weight, PHABW = prone horizontal abduction w/ cuff weight, ERB = external rotation w/ band, EXTB = extension w/ band

<table>
<thead>
<tr>
<th>Exercise</th>
<th>N</th>
<th>SLERW</th>
<th>ERB</th>
<th>PEXTW</th>
<th>EXTB</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER Pair: SLERW, ERB</td>
<td>64</td>
<td>4.41</td>
<td>5.13</td>
<td></td>
<td></td>
<td>-3.33* 0.001</td>
<td></td>
</tr>
<tr>
<td>Ext Pair: PEXTW, EXTB</td>
<td>54</td>
<td></td>
<td></td>
<td>3.67</td>
<td>3.54</td>
<td>0.490 0.626</td>
<td></td>
</tr>
</tbody>
</table>

ER Pair: SLERW, ERB
Extension Pair: PEXTW, EXTB
N=Combined surgical groups of participants performing ER Pair, Extension Pair
Abbreviations: ER = External Rotation, Ext = Extension, SLERW = sidelying ER w/ cuff weight, ERB = external rotation w/ band PEXTW = prone extension w/ cuff weight, EXTB = extension w/ band

<table>
<thead>
<tr>
<th>Exercise:</th>
<th>SLERW</th>
<th>PEXTW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance:</td>
<td>1 lb.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 lb.</td>
<td>2 lb.</td>
</tr>
<tr>
<td>N (%) ERB</td>
<td>N (%) EXTB</td>
<td></td>
</tr>
<tr>
<td>Tan TB</td>
<td>1 (6%)</td>
<td></td>
</tr>
<tr>
<td>Yellow TB</td>
<td>13 (82%)</td>
<td>7 (41%)</td>
</tr>
<tr>
<td>Red TB</td>
<td>2 (12%)</td>
<td>6 (35%)</td>
</tr>
<tr>
<td>Green TB</td>
<td></td>
<td>4 (24%)</td>
</tr>
</tbody>
</table>

Abbreviations: TB= Thera-band®, N (%) = Number of participants (percent of total), lbs. = pounds, ER = External Rotation, Ext = Extension, SLERW = sidelying ER w/ cuff weight, ERB = external rotation w/ band PEXTW = prone extension w/ cuff weight, EXTB = extension w/ band
The current study found, when grouping all exercise and surgical groups, an average OMNI RES score of 4.5 ± 2.1, with individual exercise averages ranging from “somewhat easy” to “somewhat hard” (3.6-5.7). Of note, average perceived exertion across all exercise was found to be similar between labral repair (5.2 ± 2.1), RC repair (4.7 ± 2.2), and SA groups (4.2 ± 2.1). Therefore, clinicians can expect similar RPE scores following the completion of the selected exercise regardless of the specific surgery requiring rehabilitation.

In a clinical commentary on rehabilitation after arthroscopic rotator cuff repair, van der Meijden et al10 suggests that exercises showing low muscle activation, per EMG, should be selected in early stages, and strengthening exercises shown to have higher EMG values be introduced later in the rehabilitation process. If relatively low EMG activation is a goal for early rotator cuff loading exercise, the ability of a perceived exertion scale, such as OMNI-RES, to predict muscle activation would be clinically useful and desirable, especially when simultaneous EMG is not being utilized. Morishita et al30 evaluated all current evidence on the relationship between RPE scales and load intensity during resistance training. During resistance exercise, increased ratings of exertion were found to accompany increased percentage of maximum voluntary contraction (%MVC),20,31,32 number of repetitions performed,33 EMG activity,33,34 and isometric torque.35 While there is no literature to support the use of RPE scales to guide the

<table>
<thead>
<tr>
<th>Surgical Group</th>
<th>Labral Repair</th>
<th>RTC Repair</th>
<th>Shoulder Arthroplasty</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Mean</td>
<td>N</td>
<td>Mean</td>
</tr>
<tr>
<td>1. SLERW</td>
<td>10</td>
<td>5.0±2.5</td>
<td>20</td>
</tr>
<tr>
<td>2. EROB</td>
<td>8</td>
<td>6.3±2.7</td>
<td>13</td>
</tr>
<tr>
<td>3. ERRB</td>
<td>7</td>
<td>4.7±1.8</td>
<td>10</td>
</tr>
<tr>
<td>4. PEXTW</td>
<td>9</td>
<td>3.3±1.9</td>
<td>16</td>
</tr>
<tr>
<td>5. PHABW</td>
<td>7</td>
<td>4.8±1.6</td>
<td>8</td>
</tr>
<tr>
<td>6. ERB</td>
<td>10</td>
<td>5.2±2.3</td>
<td>8</td>
</tr>
<tr>
<td>7. EXTB</td>
<td>10</td>
<td>5.2±2.1</td>
<td>8</td>
</tr>
</tbody>
</table>

N—Participants in each surgical group performing exercise at all post-operative timepoints
Mean—Average OMNI RES ± Standard Deviation
Abbreviations: SLERW = side-lying ER w/ cuff weight, EROB = external rotation oscillation w/ band, ERRB = external rotation and retraction w/ band, PEXTW = prone extension w/ cuff weight, PHABW = prone horizontal abduction w/ cuff weight, ERB = external rotation w/ band, EXTB = extension w/ band

DISCUSSION
When first introducing load to the shoulder of a post-operative patient, it is important to select low-level exercise with light resistance in attempt to protect healing structures.7,10,23 Currently, a patient’s subjective rating of exertion during or following exercise is not typically or perhaps seldomly utilized to inform or guide appropriate therapeutic exercise prescription for shoulder rehabilitation or in orthopedic practice in general, despite the high potential value for use as a reliable and valid predictor of physiologic response to exercise.17,18,29 Given the general agreement across authors in support of a gradual rotator cuff exercise loading progression in the rehabilitation of the post-operative shoulder,7,10,23 the results of this study can be used to inform clinicians of several exercises deemed to be low-to-moderate intensity per patient reported OMNI-RES scores. The current study found, when grouping all exercise and surgical groups, an average OMNI RES score of 4.5 ± 2.1, with individual exercise averages ranging from “somewhat easy” to “somewhat hard” (3.6-5.7). Of note, average perceived exertion across all exercise was found to be similar between labral repair (5.2±2.1), RC repair (4.7±2.2), and SA groups (4.2±2.1). Therefore, clinicians can expect similar RPE scores following the completion of the selected exercise regardless of the specific surgery requiring rehabilitation.

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Table 7. OMNI RES Averages by Surgical Intervention.
post-operative management of patients with shoulder pathology, the studies previously mentioned support the concept of a patient report of muscle work playing a role in clinical decision making among other factors such as physician protocol, surgical technique, tissue quality, post-operative time-point, patient pain response, age, comorbidities, etc.

Shoulder external rotation exercises in standing using elastic resistance (ERB) and in sidelying with cuff weights (SLERW) are commonly employed in clinical practice to activate and primarily strengthen the shoulder external rotator muscles. When compared, free weight and TB resistance training have been shown to equivalently improve isometric strength in short-term resistance exercise programs. With comparison of RPE of the external rotation exercise pair, the current study found ERB to be rated significantly higher than SLERW (OMNI-RES average: 5.13, 4.41, respectively p = 0.001). Of note, the clinical relevance of an OMNI-RES score comparison between two exercises found to be less than one point apart is currently unknown, but it is the opinion of the authors that these exercises can be considered highly similar in exertion levels. Andersen et al also studied RPE (Borg CR-10) in this external rotation pairing with matching resistance for dumbbell and TB exercise (example: Red TB = 2.0-2.2 kg, dumbbell = 2.0 kg), Green TB = 2.6-3.0, dumbbell = 3.0kg, etc.). Both this, and the current studies found low to moderate average RPE values for ERB and SLERW and small relative differences in RPE between such exercises (Average Borg CR-10 difference between ERB and SLERW: Red TB/2 kg: (0.5), Green TB/3 kg: (0.8)).

OMNI-RES score averages across all exercises and surgical groups were found to be similar when comparing the 6- and 12-week post-operative time points with the AMD of a selected exercise ranging from (0.1-1.2). During the course of rehabilitation for patients in the current study regularly attending physical therapy at a private outpatient orthopedic clinic, resistance for a given exercise was increased when appropriate with consideration of post-operative tissue-healing stage, pain, RPE, etc. Therefore, higher TB/cuff weight resistance was used at the 12-week versus 6-week post-operative timepoint despite similar OMNI-RES scores. As previously stated, studies of healthy, non-surgical, non-rehabilitation research volunteers of varying age have reported a consistent increase in RPE with an increase in resistance for a given exercise. Improvements in strength and pain levels in the 6 week interval between data collection may explain this observed rise in exercise resistance without concomitant rise in OMNI-RES score in the current study.

The present study is the first to collect ratings of RPE for commonly prescribed rotator cuff and scapular stabilizer exercises selected for rehabilitation in a surgical cohort including labral repair, RC repair, and SA. While this study can inform clinicians of expected OMNI-RES scores following exercise for similar patients, future research on ideal exercise exertion levels for patients in early, middle, and late-stage rehabilitation programs would be of high value. The addition of patient RPE with resistive exercise as a factor used to guide post-operative shoulder rehabilitation may offer utility knowing the reported linear relationship between RPE, resistance level, % MVC, EMG activity, joint torque, and number of repetitions. If clinicians can use RPE ratings as a way to examine appropriateness of an exercise, this may provide additional objective monitoring alongside biofeedback and dynamometry. Future research on correlating joint loading, EMG levels and RPE during common shoulder strengthening exercises in a post-operative cohort could serve to confirm the concept of low RPE ratings during exercise with low risk of compromising a surgical repair and allow the formation of groups of exercise/exercise resistance to be employed at certain stages of rehabilitation.

Limitations of this clinically based study primarily include the application of findings limited to a post-operative shoulder patient group under the direction and care of one physical therapist. While certain surgery-specific cohort participant numbers were relatively small, when taken as a single post-operative cohort of 66 participants, stronger conclusions can be made from the descriptive information presented in this study.

CONCLUSION

Commonly prescribed resistance exercise in the rehabilitation following shoulder surgery show light-moderate ratings of perceived exertion using
the OMNI-RES rating scale at both 6- and 12-week post-operative timepoints across three surgical procedures.

REFERENCES


ORIGINAL RESEARCH
THE RELATIONSHIP BETWEEN SINGLE LEG BALANCE AND ISOMETRIC ANKLE AND HIP STRENGTH IN A HEALTHY POPULATION

Hanz Tao, PT, DPT, SCS, CSCS1
Anthony Husher, PT, DPT, CSCS1
Zachary Schneider, PT, DPT1
Scott Strand, PT, DPT1
Brandon Ness, PT, DPT, SCS, CSCS1,2

ABSTRACT

Background: Impaired balance and strength commonly affect athletes with conditions like chronic ankle instability (CAI). Yet, clinical research surrounding the relationship between balance, strength, and CAI is still growing. Deeper investigation of these relationships is warranted to better inform clinical practice patterns when managing athletes with balance deficits.

Purpose: To investigate the relationship between single leg balance, ankle strength, and hip strength in healthy, active adults.

Study Design: Observational study

Methods: Forty healthy participants (age 23.7 ± 4.9 years) were assessed for static balance, using a modified version of the Balance Error Scoring System (mBESS), as well as isometric strength of ankle and hip musculature via handheld dynamometry. Pearson’s correlations were used to analyze relationships between balance and strength measures. Paired t-tests were utilized to compare dominant and non-dominant limb performance.

Results: Negligible to low, negative correlations were found between balance scores and hip extension strength ($r = -0.24$ to $-0.38$, $p<0.05$). High, positive correlations were found between ankle and hip strength measures ($r = 0.75$ to $0.84$, $p<0.05$). When comparing dominant to non-dominant limbs, only minimal differences were noted in ankle eversion strength (mean difference = 6.0%, $p<0.01$) and hip extension strength (mean difference = 5.5%, $p<0.01$).

Conclusions: Minimal relationships were identified between static balance and isometric ankle and hip strength. Comparison of dominant and non-dominant limbs suggests that clinicians should expect relative symmetry in balance and strength in healthy adults. Thus, asymmetries found during clinical examination should raise suspicion of specific impairments that may lead to dysfunction.

Level of Evidence: 2c

Keywords: balance, hip strength, ankle strength, chronic ankle instability, ankle sprain, movement system

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2 Doctor of Physical Therapy Program, Department of Public Health and Community Medicine, Tufts University School of Medicine, Boston, MA, USA

IRB Approval: The study protocol was approved by the University of South Dakota Institutional Review Board (IRB) on July 25, 2017: Project 2017.145.

Financial Disclosures: Brandon Ness is an instructor for a continuing education company and receives honorariums for teaching courses related to sports physical therapy, is in the process of commercializing a rehabilitation measurement device.

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INTRODUCTION
In high school sports, ankle sprains account for 16% of all injuries, at a rate of 3.65 sprains per 10,000 athlete exposures. Residual symptoms following ankle sprains include pain, instability, swelling, and recurrent sprains, leading to chronic ankle instability (CAI). In fact, high school athletes with prior ankle injuries are 4.22 times more likely to suffer a second ankle injury, compared to those without a history of injuries. Several risk factors have been hypothesized to contribute to the development of CAI, including impairments of balance, neuromuscular control, hip strength, ankle strength, and ankle range of motion.

Balance is a sensorimotor process aimed at maintaining, achieving, or restoring a state of stability during activity. It involves synchrony between proprioceptive, somatosensory, vestibular, visual, and neuromuscular systems. An athlete’s ability to maintain balance on one leg, known as single leg balance (SLB), has been linked to ankle injuries. McGuine et al found that high school basketball players who demonstrated poor SLB were 6.7 times more likely to sustain ankle injury than those with good balance. Similarly, Trojan et al found that athletes with poor SLB who did not receive in-season ankle taping were 8.82 times more likely to sustain an ankle injury. Therefore, assessing SLB can provide meaningful information about injury risk.

Methods
Design
The study protocol was approved by the University of South Dakota Institutional Review Board. All participants signed an approved informed consent form prior to participation. The study utilized a correlational study design comparing balance to ankle and hip strength in healthy, active adults.

Participants
All participants were recruited from a sample of convenience at a Midwestern university. Inclusion criteria were: age between 18-64 years, English-speaking, and a score of 5 or greater on the Tegner Activity Scale (indicating a minimum activity level of jogging twice weekly). Exclusion criteria were: pregnancy, known balance impairment (unresolved head injuries, vertigo, recent head cold, etc), or a lower extremity injury in the prior six months.

Procedures
Demographic information was collected, including age, height, weight, gender, dominant leg, activity level, and lower extremity injury history. Participants completed a five-minute warm-up on a stationary bicycle at a light to moderate intensity. Next, participants were asked to remove footwear and socks, and randomly assigned to one of three stations: balance, ankle strength, and hip strength in healthy, active adults.
hip strength. Once testing was completed at each station, participants proceeded to subsequent stations in stepwise fashion. Examiners at each station provided standardized verbal instructions. At each station, one examiner was responsible for testing all participants in order to reduce errors from examiner agreement. Examiners were blinded from the participants’ results in other stations. Intra-rater reliability was calculated for each test using intraclass correlation coefficients (ICC) with 95% confidence intervals, based on a single rater, single measurement, absolute agreement, two-way mixed-effects model. Strength of reliability was defined as: <0.5 (poor), 0.5-0.75 (moderate), 0.75-0.90 (good), and 0.90-1.0 (excellent).

**Modified Balance Error Scoring System (mBESS)**

The original BESS, which also includes double limb and tandem stances, has been reported with moderate to excellent intra-rater reliability (ICC = 0.60-0.92), moderate to good inter-rater reliability (ICC = 0.57-0.85), and moderate test-retest reliability (ICC2,1 = 0.70). Individual single leg balance scores have been reported with moderate to excellent intra-rater reliability (ICC = 0.50-0.95) and moderate to good inter-rater reliability (ICC = 0.53-0.83). Docherty et al found that individuals with CAI had worse scores on the specific single leg balance items. Therefore, a modified version of the test (mBESS), consisting of only the single leg balance items, was used in this study.

The mBESS consisted of a single leg balance test on stable and unstable surfaces (Figure 1). First, participants stood on one leg, placed hands on their hips, and were asked to maintain balance with eyes closed for 20 seconds. Next, participants repeated the task on a foam pad (6 cm thickness, Airex AG, Switzerland). The examiner provided verbal and visual instruction and scored the tests in real time. Each of the following errors represented one point: opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting the hip by more than 30°, or failing to return to the test position in more than five seconds. Participants were allowed one practice trial, followed by two scored trials for each task. Right and left limbs were tested in random order. A 10-second rest period was provided between trials. For each limb, the average of the two trials was scored under the stable (ground) and unstable (foam pad) conditions. The mBESS score for each limb equaled the sum of stable and unstable scores. Intra-rater reliability was moderate for stable (ICC = 0.54; 95% CI: 0.37-0.68), unstable (ICC = 0.73; 95% CI: 0.61-0.82), and composite mBESS scores (ICC = 0.71; 95% CI: 0.58-0.80).

**Strength Measures**

For all strength measures, examiners utilized a digital hand-held dynamometer (HHD; MicroFET 2, Hoggan Scientific LLC, Salt Lake City, UT) to measure torque (Nm). Examiners marked locations, specified below, to consistently apply a downward force for five seconds or until the participants could not sustain the hold any longer. Right and left limbs were tested in random order. Three successful trials were recorded on each limb, with a 10-second rest period between tests. The average of three trials for each limb was converted to a torque-to-body weight (T:BW) value.

**Isometric Ankle Strength**

Isometric ankle strength was assessed using modified MMT techniques (Figure 2). For ankle inversion,
participants were positioned on their side with the ankle in a resting position (approximately 10-20° of ankle plantarflexion, neutral inversion-eversion). The examiner marked on the medial aspect of the foot, 5 cm proximal to the head of the first metatarsal, to be used as the point of applied force during the MMT. The examiner measured the distance between this point and the ankle joint axis to record the moment arm. Next, the examiner placed the HHD on the mark and applied a downward force to obtain the strength measurement.

For ankle eversion strength, participants were positioned on their opposite side with their pelvis stabilized to the table using a belt. The examiner marked 10 cm proximal to the knee joint axis on the posterior thigh, to be used as the point of applied force during the MMT, then measured the distance between this point and the hip joint axis to record the moment arm. Next, the examiner identified a mid-range of hip extension, placed the HHD on the mark, and applied a downward force to obtain the strength measurement.

For hip extension strength, participants were positioned in prone with their pelvis stabilized to the table using a belt. The examiner marked 10 cm proximal to the knee joint axis on the posterior thigh, to be used as the point of applied force during the MMT, then measured the distance between this point and the hip joint axis to record the moment arm. Next, the examiner identified a mid-range of hip extension, placed the HHD on the mark, and applied a downward force to obtain the strength measurement.

For hip abduction strength, participants were positioned on their side with their pelvis stabilized to the table using a belt. The examiner marked 5 cm proximal to the lateral femoral condyle, to be used as the point of applied force during the MMT. The examiner measured the distance between this point and the hip joint axis to record the moment arm. The participants abducted their tested hip with the knee extended. The examiner identified a mid-range of hip abduction, placed the HHD on the mark, and applied a downward force to obtain the strength measurement. Intra-rater reliability was excellent for hip extension (ICC = 0.93; 95% CI 0.90-0.95) and abduction (ICC = 0.91; 95% CI 0.87-0.94).

Data Analysis
Results from the mBESS composite score, stable and unstable balance scores, and isometric ankle and hip strength were analyzed using SPSS Statistics.
A significance of $\alpha = 0.05$ was set for all analyses. Pearson’s correlation ($r$) tests were utilized to analyze the relationship between balance and strength measures, as well as between individual strength measures. Strength of correlations were defined as: $<0.30$ (negligible), $0.30-0.50$ (low), $0.50-0.70$ (moderate), $0.70-0.90$ (high), and $0.90-1.0$ (very high). Paired t-tests compared balance and strength results between dominant and non-dominant limbs. The effect size of limb dominance was calculated by Cohen’s $d$. An $a$ priori power analysis revealed that 34 participants were needed to achieve an 80% study power with $\alpha$ error probability of 0.05 and effect size of $d = 0.50$.

RESULTS

Forty participants (age: $23.7 \pm 4.9$ years; 55% female; Tegner score: $6.9 \pm 1.5$) were included in data analysis. Descriptive statistics are highlighted in Table 1. Participants averaged $2.23 \pm 1.57$ errors per limb while balancing on a stable surface and $6.95 \pm 1.77$ errors per limb on an unstable surface, translating to an average mBESS score of $9.18 \pm 2.90$ errors per limb. Regarding ankle strength, participants averaged $0.33 \pm 0.05$ Nm/kg and $0.39 \pm 0.05$ Nm/kg of inversion and eversion strength, respectively. For hip strength, participants averaged $1.25 \pm 0.34$ Nm/kg and $1.65 \pm 0.29$ Nm/kg of extension and abduction strength, respectively.

Table 2 lists the results of the correlation analysis between balance and strength measures. There were negligible to low, negative correlations between balance tests and hip extension strength ($r = -0.24$ to $-0.38$, $p<0.05$). Higher scores (errors) on balance tests were associated with lower hip extension strength. That is to say, participants with worse single-leg balance were more likely to have weaker hip extension strength. No other significant correlations between balance and strength were observed.

Correlation matrices between ankle and hip strength are displayed in Table 3. There were low to moderate correlations between all T:BW values ($r = 0.32$ to 0.53, $p<0.01$) and high correlations between all torque values without bodyweight adjustment ($r = 0.75$ to 0.84, $p<0.01$).

Comparison of dominant and non-dominant limbs are summarized in Table 4. Limb dominance had medium effects on hip extension and ankle eversion strength ($d = 0.75$ and 0.77, respectively), and a large effect on ankle eversion:inversion (E:I) ratio ($d = 0.86$). The dominant limb tested 5.5% stronger than the non-dominant limb for hip extension (mean difference: $0.07$ Nm/kg, 95% CI $0.02-0.12$) and 6.0% stronger for ankle eversion (mean difference: $0.02$ Nm/kg, 95% CI $0.01-0.04$). The E:I ratio was also higher on the dominant limb ($p<0.01$). No other measures demonstrated a significant difference in limb dominance.

DISCUSSION

The results in this study suggest that minimal relationship exists between static balance and isometric strength of ankle and hip musculature in healthy, active adults. Only negligible to low correlations between balance and hip extension strength were observed, while all other correlations were insignificant. Two other investigators have also examined the balance-hip strength relationship, though both used the Y-Balance Test (YBT), a measure of dynamic balance. Lee et al found that in women, high correlations existed between YBT reach distances and isometric strength of hip extensors ($r = 0.70$ to 0.75) and abductors ($r = 0.72$). Culiver et al also identified an inverse correlation between hip abduction strength asymmetry and dominant limb YBT composite score ($r = -0.46$) in Division I baseball pitchers. These higher correlations may reflect the greater demands on muscle strength during a dynamic task (YBT), compared to the static single leg balance tasks examined in this study.
between balance and lower extremity strength in children ($r = 0.11, 95\% \text{ CI} -0.18 \text{ to } 0.41$), young adults ($r = 0.20, 95\% \text{ CI} -0.02 \text{ to } 0.41$), or older adults ($r = 0.27, 95\% \text{ CI} 0.15 \text{ to } 0.40$). Lin et al\textsuperscript{33} and Nonetheless, the primary results mirror the conclusions made by a majority of researchers on healthy individuals.\textsuperscript{32-35} In a meta-analysis, Muehlbauer et al\textsuperscript{32} concluded that little to no correlations existed between balance and lower extremity strength in children ($r = 0.11, 95\% \text{ CI} -0.18 \text{ to } 0.41$), young adults ($r = 0.20, 95\% \text{ CI} -0.02 \text{ to } 0.41$), or older adults ($r = 0.27, 95\% \text{ CI} 0.15 \text{ to } 0.40$). Lin et al\textsuperscript{33} and

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**Table 2. Pearson correlation ($r$) results between balance testing and torque to body weight strength measures (Nm/kg)**

<table>
<thead>
<tr>
<th></th>
<th>Hip Extension</th>
<th>Hip Abduction</th>
<th>Ankle Inversion</th>
<th>Ankle Eversion</th>
<th>Ev:Inv Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>mBESS</td>
<td>-0.36*</td>
<td>-0.10</td>
<td>-0.07</td>
<td>-0.19</td>
<td>-0.08</td>
</tr>
<tr>
<td>SLB Stable</td>
<td>-0.24*</td>
<td>-0.83</td>
<td>-0.39</td>
<td>-0.13</td>
<td>-0.06</td>
</tr>
<tr>
<td>SLB Unstable</td>
<td>-0.38*</td>
<td>-0.10</td>
<td>-0.08</td>
<td>-0.19</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

* Indicates a significant correlation ($p<0.05$); † Indicates a significant correlation ($p<0.01$).

**Table 3a. Pearson correlation matrix ($r$) between torque to body weight values (Nm/kg) of hip and ankle.**

<table>
<thead>
<tr>
<th></th>
<th>Hip extension</th>
<th>Hip abduction</th>
<th>Ankle inversion</th>
<th>Ankle eversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip extension</td>
<td>1</td>
<td>0.41†</td>
<td>0.32†</td>
<td>0.46†</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>1†</td>
<td>1</td>
<td>0.47†</td>
<td>0.43†</td>
</tr>
<tr>
<td>Ankle inversion</td>
<td>1</td>
<td>1</td>
<td>0.53†</td>
<td>1</td>
</tr>
</tbody>
</table>

† Indicates a significant correlation ($p<.01$).

**Table 3b. Pearson correlation matrix ($r$) between torque values (Nm) of hip and ankle strength tests.**

<table>
<thead>
<tr>
<th></th>
<th>Hip extension</th>
<th>Hip abduction</th>
<th>Ankle inversion</th>
<th>Ankle eversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip extension</td>
<td>1</td>
<td>0.75†</td>
<td>0.75†</td>
<td>0.82†</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>1†</td>
<td>1</td>
<td>0.79†</td>
<td>0.78†</td>
</tr>
<tr>
<td>Ankle inversion</td>
<td>1</td>
<td>1</td>
<td>0.84†</td>
<td>1</td>
</tr>
</tbody>
</table>

† Indicates a significant correlation ($p<.01$).

**Table 4. Statistical comparisons of test scores between dominant and non-dominant limb. Strength value differences are expressed as torque to body weight (Nm/kg)**

<table>
<thead>
<tr>
<th></th>
<th>Percent Change</th>
<th>Mean Difference</th>
<th>95% Confidence Interval</th>
<th>T-score</th>
<th>Cohen’s $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>Upper</td>
<td></td>
</tr>
<tr>
<td>mBESS</td>
<td>NA</td>
<td>-0.01</td>
<td>-0.60</td>
<td>0.57</td>
<td>-0.43</td>
</tr>
<tr>
<td>SLB Stable</td>
<td>NA</td>
<td>0.16</td>
<td>-0.23</td>
<td>0.55</td>
<td>0.84</td>
</tr>
<tr>
<td>SLB Unstable</td>
<td>NA</td>
<td>-0.18</td>
<td>-0.59</td>
<td>0.24</td>
<td>-0.86</td>
</tr>
<tr>
<td>Hip Extension</td>
<td>5.5%</td>
<td>0.07†</td>
<td>0.02</td>
<td>0.12</td>
<td>3.35</td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>1.8%</td>
<td>-0.03</td>
<td>-0.09</td>
<td>0.03</td>
<td>-0.14</td>
</tr>
<tr>
<td>Ankle Inversion</td>
<td>3.3%</td>
<td>-0.01</td>
<td>-0.02</td>
<td>0.00</td>
<td>-1.73</td>
</tr>
<tr>
<td>Ankle Eversion</td>
<td>6.0%</td>
<td>0.02†</td>
<td>0.01</td>
<td>0.04</td>
<td>3.43</td>
</tr>
<tr>
<td>E:1 Ratio</td>
<td>NA</td>
<td>0.12†</td>
<td>0.06</td>
<td>0.18</td>
<td>3.83</td>
</tr>
</tbody>
</table>

mBESS = modified balance error scoring system; SLB = single leg balance; E:1 = Eversion:Inversion

† Indicates a significant difference ($p<.01$).
A sound biomechanical explanation requires a deeper investigation beyond the scope of this study, the results have important clinical implications. First, clinicians may save time by calculating strength as a torque value, rather than normalizing torque to body weight. Second, clinicians should expect that if an individual tests strongly in one muscle group, then they should test proportionately strong in other areas around the ankle and hip. Any disproportionate weakness may indicate an abnormal finding.

Regarding limb dominance, no asymmetries were detected in mBESS or static balance on stable and unstable surfaces. These results are met with mixed conclusions by other investigators. Alonso et al. found that males aged 20-40 years had no limb asymmetries in balance, which was tested on a Biodex Balance System. In healthy adults (females and males), Lin et al. found no limb asymmetries in balance using a force platform. In contrast, Dabadghav found that basketball players had lower radial displacement while balancing on their dominant limb, as tested on a force platform. Additionally, Promsri et al. reported that young, active adults prioritized different motor control strategies between dominant and non-dominant limbs, using a 3-dimensional motion capture system. However, they found no differences in the overall coordinative structure of balance. These conflicting results may be due to differences in population, testing procedures, or data analysis. First, basketball players may represent a unique population due to the postural demands of the sport. Secondly, researchers used varying methods to determine the “dominant limb.” Thirdly, balance testing varied between studies, ranging from a 10-second test under stable conditions to a 20-second eyes closed test on an unstable surface. Finally, robust data capturing systems were able to identify more specific differences in balance (i.e. motor control). Yet, the clinical relevance of this detail must be further investigated. In general, limb asymmetries should not be expected in healthy individuals when clinically testing SLB.

In this study, the dominant limb tested slightly stronger than the non-dominant limb for ankle eversion (6.0%), but not inversion. This corresponded to a significant increase in E:I ratio. This conflicts with conclusions by Dabadghav and Lin et al., who did not
not detect asymmetries in eversion strength, inversion strength, or E:I ratios. The small differences in this study may be related to testing methods. This study used isometric strength tests, whereas the two other authors utilized isokinetic tests. This increased the overall E:I ratios to 1.19 ± 0.16, which was higher than other reported ratios (0.80-1.06) in healthy individuals.33, 34 Interestingly, Lin et al33 identified a significant pattern that slower isokinetic testing speeds resulted in higher E:I ratios. This might explain why isometric testing shifted the ratios in this study toward eversion. Despite differences, the overall relationship between limb dominance and ankle strength is minimal at best.

In the current study, hip extension strength tested slightly stronger in the dominant limb (5.5%), while hip abduction strength did not reveal any asymmetries. Lopes et al61 reported that healthy, male Navy cadets had slightly stronger dominant limb hip external rotation strength by 7.7% (p ≤ 0.05), whereas female cadets did not. Neither gender had differences in hip abduction strength. It is possible that the gluteus maximus, which is responsible for both hip extension and external rotation, may reveal limb dominance patterns, albeit minimal. However, the gluteus medius does not appear to be affected by limb dominance in healthy adults.

In summary, limb asymmetry during static balance and strength testing (generally >6%) should not be explained by limb dominance. Furthermore, ankle and hip muscles should test proportionately strong. It is plausible for clinicians to interpret asymmetrical balance or strength, and disproportionate ankle or hip strength, as abnormal. Finally, the minimal relationship between balance and strength measures serves as a reminder of the complex, multifactorial nature of maintaining balance. Thus, treatment of balance and strength impairments should be individually tailored and complimentary in nature.

Limitations

The study collected data from a relatively small sample of healthy, active adults, thus limiting generalizability to a wider population. It is possible that test selection may have limited the results. For example, the mBESS may have both floor and ceiling effects which require further investigation. Despite this, the mBESS was selected because of its ability to efficiently quantify balance impairments with minimal equipment expense. Finally, the observational nature of this study should preclude the claim of any causal relationships.

CONCLUSION

In healthy, active adults, there is minimal relationship between static balance and isometric ankle or hip strength. However, high correlations exist between all ankle and hip strength measures. Furthermore, limb dominance does not seem to significantly impact performance on most tests, and at most explains a 6% asymmetry in strength. Therefore, in individuals with anticipated balance deficits, such as those with CAI, it is important for clinicians to assess and treat each impairment independently, using disproportionate weakness and/or asymmetry as a valid finding.

REFERENCES


ABSTRACT

**Background:** Using 3-dimensional motion analysis to derive knee moments that may contribute to non-contact anterior cruciate ligament (ACL) injuries during single-leg jump-landing is expensive and time consuming. Severe ACL injuries that are inappropriately rehabilitated can potentially end athletes' careers. Consequently, a quick-and-simple to administer screening tool that can be used to infer knee moments during single-leg jump-landing could be useful for regular screening of netballers' predispositions to increased knee loading during single-leg jump-landing.

**Purpose:** The purpose of this study was to investigate whether knee moments during weight-acceptance phase of a forward single-leg jump for maximal distance were correlated with reach scores in the Y-Balance Test (YBT).

**Study Design:** Cross-sectional, Correlation.

**Methods:** Twenty-one female national-level netballers performed two and three successful trials on the YBT and forward single-leg jump-landing, respectively, with the non-dominant leg. A three-dimensional motion analysis system captured trunk and lower limb kinematics and ground reaction forces of the non-dominant leg during landing. Averages of peak knee flexion-extension, valgus-varus and internal-external rotation moments across jumps were calculated and correlations with peak directional reach scores were examined.

**Results:** A strong positive correlation existed between posteromedial reach with externally applied flexor moments ($r = 0.56, p = ≤ 0.01$). A moderate negative correlation existed between anterior reach distances with internal rotation moments ($T_b = -0.32, p = 0.05$). No correlation was found between valgus moments and YBT reaches.

**Conclusions:** The YBT shows potential to indicate externally applied flexion- and internal rotation moments during forward jump-landing on the non-dominant leg.

**Level of Evidence:** 3

**KeyWords:** Jump landing, knee moments, Netball, movement system, Y-balance test
INTRODUCTION

Single-leg jump-landing and sidestepping are common in team sports like basketball and netball and contribute to majority of non-contact ACL injuries. These movements can result in large externally applied flexion, internal rotation and valgus moments at the knee joint that can strain the ACL if one displays poor neuromuscular control of the lower extremities during dynamic movements. A cadaveric study using simulated jump landing found that the independent increment of internal rotation and valgus moments strained the ACL more than flexion moments, with the combination of all three straining the ACL the most. A ruptured ACL can be detrimental to an athlete’s sporting career as it takes six to twelve months of rehabilitation before return to sport.

Females are four to six times more likely to sustain a non-contact ACL injury than males due to anatomical, hormonal and neuromuscular reasons, especially on their non-dominant leg. Netball, commonly participated in by females, contributes to high rates of non-contact ACL injury mainly from jump landing and sidestepping. In a study reviewing ACL injury occurrences, 21 out of 29 incidences occurred at initial foot contact during single-leg weight bearing activities. Compared with double-leg landings, single-leg jump-landing was reported to result in greater knee valgus and reduced knee flexion angles, both contributors to non-contact ACL injuries. The strict footwork rules that require netballers to stop within one and a half steps upon landing on one leg restricts attenuation time and increases the rate of loading on the knee compared with taking an additional step, thereby increasing the risk of lower limb injuries. With over 20 million people around the world playing netball, regular screening for ACL injury risk is vital.

The current gold standard for measuring knee joint moments during sporting movements involve the use of three-dimensional (3D) motion analysis systems; an expensive and time-consuming process that is unavailable to many. There is an increasing demand for simple-to-administer screening tools to replace sophisticated laboratory-based tests that are used to assess movement and by inference, sporting performance and injury risk. The Landing Error Scoring System and Tuck Jump Assessment assess knee flexion and valgus angles during double-legged landing to identify high-risk movement patterns that may injure the ACL. These assessment tools require assessors to be proficient in using two-dimensional video cameras to film knee movements in the sagittal and frontal planes, and identify specific anatomical landmarks on the lower limbs to assess knee movements in a valid and repeatable manner. These requirements are not trivial and if not met may misrepresent injury risks. Furthermore, these tools do not assess knee rotation; one of three knee movements that can strain the ACL. In another study, Myers and colleagues suggested that reach distances achieved by patients post-ACL reconstruction during the simple-to-administer Y-Balance Test (YBT) could periodically be monitored to assess their readiness to return-to-sport, as reach scores had moderate to strong correlations with peak isokinetic knee flexion-extension torques assessed using a laboratory-based dynamometer. In the context of this study, it would be beneficial to identify a simple-to-administer screening tool that is representative of knee joint moments as assessed by a 3D motion analyses system during single-leg jump-landing.

The YBT is a simple-to-administer screening tool that assesses single-leg dynamic balance; a performance variable that associates with lower limb injury risk in athletes, with high inter- (ICC: 0.99 – 1.00) and intra-rater reliabilities (ICC: 0.85 – 0.91). Participants reach maximally in three directions (anterior, posteromedial and posterolateral) with each leg, and the distances achieved by the leg that reaches reflect the stance leg’s functional strength and range of motion. Asymmetries in reach distances between legs have been linked with higher injury risk of the lower limbs although the types of injuries have not been specifically identified. While one leg is reaching, especially in the anterior direction, the stance leg lowers the body like a single-leg squat movement. The posteromedial and posterolateral reaches add variability to the knee loading patterns of the stance leg due to the different postural requirements to reach maximally. Fox, Bonacci & Saunders reported that single-leg squat performances can be used to predict ACL injury risk during leap-landing in netball and should be administered as a regular screening tool for netballers. Other researchers have, similarly, reported the...
potential for the YBT to assess presence of specific lower limb injuries such as chronic ankle instability and strength imbalances between uninjured and ACL-reconstructed knees.15,23 This raised the question: ‘Can the YBT be used to indicate the risk of knee injuries by way of inference to knee moments during single-leg jump-landing?’

The purpose of this study was to investigate whether knee moments during weight-acceptance phase of a forward single-leg jump for maximal distance were correlated with reach scores in the YBT. The presence of correlations may identify a screening tool that can be used to infer knee moments during single-leg jump-landing in netball and by extension, risk for non-contact ACL injury.

METHODS

Participants
Twenty-one female netballers (age: 23.2 ± 3.8 y; height: 1.73 ± 0.1 m; mass: 62.7 ± 5.1 kg) were recruited from the Singapore national team. All participants had no pre-existing lower limb injury and were proficient in reaching maximally on the YBT and performing single-leg jump-landings with their non-dominant leg. Participants were briefed that they would perform both the forward single-leg jump-landing for maximal distance and YBT with the order randomized to eliminate sequencing effects. For this correlational study, a minimum of 19 subjects were necessary to achieve a statistical power of 0.8 and p < 0.05. All procedures and forms were approved by the Singapore Sport Institute Institutional Review Board, and all participants provided their informed written consent before data was collected.

Instrumentation & Procedures
Participants were required to perform forward single-leg jumps for maximal distance (Figure 1), pushing off with their dominant leg and landing within the force platform with their non-dominant leg. Participants verbally indicated their preferred leg to push-off after performing a self-selected number of single-leg jumps. This leg was determined as the participants’ dominant leg while the other leg was determined as their non-dominant leg for the single-leg jump-landings. Maximal jump distances were ascertained by asking participants to jump slightly further each time until they reached a distance that they could not improve on in two subsequent jumps during familiarization. A cone was used to demarcate each individual’s starting position from the force platform based on the maximal jump distances achieved during familiarization. After familiarization, participants performed three test trials. A trial was considered successful when participants were able to maintain balance upon landing for at least 2 seconds and had their foot planted within the area of the force platform.24 Thirty seconds of rest between trials was provided to prevent fatigue from affecting performance.24

Although the single-leg hop test, which involves a participant pushing off and landing on the same leg while trying to cover maximal distance, has been reported to reliably assess lower limb function and return-to-sport readiness post-ACL injury rehabilitation,25–27 this study employed the forward single-leg jump-landing task whereby participants pushed off with their dominant leg and landed on their non-dominant leg. The single-leg jump-landing task was employed as it was deemed to be more representative of the movement performed during netball when the athlete pushes off one leg to catch or intercept a ball and lands on the other leg. As most non-contact ACL injuries occur during single-leg landing, assessment of the landing biomechanics would provide deeper insights into ACL injury risk compared to mere hop distance alone.28

Figure 1. Single-leg Jump Landing for Maximal Distance. (a) Front View, (b) Side View
Three-dimensional body kinematics during the forward single-leg jump-landing were captured using 12 Vicon 3D motion capture cameras (Vicon Industries Inc., Edgewood, NY, USA) at a sampling rate of 250 Hz. Ground reaction forces were captured synchronously at 1000 Hz using a 0.6 m by 0.9 m Kistler force platform (Kistler 9287CA Piezoelectric, Winterthur, Switzerland). Thirty-two retro-reflective markers, following the University of Western Australia (UWA) Lower Limb Model and Marker Set, were affixed to selected anatomical landmarks on each participant to facilitate 3D motion analysis. Detailed description of data collection with this marker set set-up and calibration can be found from previous research by Besier and colleagues.29

Captured kinematic and kinetic data were analyzed in Vicon Nexus (version 2.3, Oxford Metric Group, Oxford, UK). Knee joint moments were calculated through inverse dynamics, using a custom Matlab (The Mathworks, Inc., Natick, MA) program during the weight-acceptance phases for the forward single-leg jump-landing task. Output moments calculated were externally applied and as follows: flexion (+) /extension (-), valgus (+)/varus (-), internal rotation (+)/external rotation (-). Marker trajectories and force plate data were filtered with a low-pass (4th order, zero-lag) Butterworth digital filter at a cut-off frequency of 18 Hz after residual analysis and visual inspection of the data. Peak values for externally applied knee flexor-, valgus- and internal rotation-moments were ascertained from each trial. Knee moments for all participants were normalized to height and mass, and presented as the mean of peaks from three successful trials.

Participants performed the YBT (Perform Better Inc, Cranston, RI) (Figure 2), a test of single-leg dynamic balance before or after performing the forward single-leg jump-landing. Participants were required to balance on their non-dominant leg, barefooted, and push the measurement blocks as far as possible with their dominant leg. The distances achieved by the dominant leg that is reaching were dependent on the functional strength and range of motion of the non-dominant leg in unilateral stance. A trial was voided and retaken if the participant (1) failed to maintain unilateral stance, (2) lifted the stance foot from the platform, (3) failed to maintain constant reach on the block while it was in motion, (4) used the block for support, or (5) lifted arm(s) off the hips. Sequences of directions were randomized and counterbalanced to minimise sequencing effects. Four familiarization and two successful trials in all directions were required from all participants. Familiarization was necessary to achieve maximal reach distances and remove learning effects during test trials. Length of the non-dominant leg was measured with participants in supine, from the anterior-superior iliac spine to lateral malleolus, using a standard cloth tape measure and used for normalisation of reach scores. Maximal reach distances of the dominant leg; while balancing on the non-dominant leg; in all three directions were measured to the nearest half-centimetre. Reach distances were normalised to limb length and multiplied by 100 for representation as a percentage.

RESULTS

Data Analysis

Linear regressions were performed to assess the predictive relationship between YBT scores and 1) PKF-, 2) PKV-, and 3) PKIR- moments using StatsDirect Statistical Software (Version 3.1.20; StatsDirect Ltd., England, UK) with significance level set at p ≤ 0.05. Simple linear regression with correlation was performed on parametric variables while the nonparametric linear regression was used for nonparametric variables, and presented as an equation with components \( b \) (median slope) and \( c \) (y-intercept). Correlation coefficients, \( r \) (Pearson’s product-moment correlation) and \( T_b \) (Kendall’s tau-b correlation coefficient), are presented for the parametric and nonparametric variables, respectively. The strength of association is as follows: 0.1 < \( r \)
< 0.3 (small correlation), 0.3 < r < 0.5 (moderate correlation), and r > 0.5 (strong correlation). Means ± standard deviations are also presented for each variable. All variables were tested for normality and outliers. Variables were considered outliers if they exceeded >3 standard deviations from the mean.32

**Descriptive Statistics**

All variables were normally distributed with the exception of PKIR that was tested using the non-parametric alternative. Table 1 presents the normalized means for YBT scores and PKF-, PKV- and PKIR-moments during forward single-leg jump-landing. Posteromedial reach was a significant and strong predictor of PKF moments, $m = 2.78$, $c = -1.01$, $p < 0.01$, $r = 0.56$, with simple linear regression equation estimated as PKF = 2.78*(posteromedial) – 1.01 (Figure 3a). Anterior reach was a significant and moderate predictor of PKIR moments, $b = -1$, $c = 0.84$, $p = 0.05$ with the stepwise-regression equation estimated as PKIR = -1*(anterior) + 0.84, $T_b = -0.32$ (Figure 3b). There were no significant relationships between PKV moments and individual reach scores ($0.15 < p < 0.92$).

**DISCUSSION**

This exploratory study investigated whether scores on the YBT were correlated with PKF-, PKV- and PKIR moments during a forward single-leg jump-landing for maximal distance of the non-dominant leg. Moderate to strong correlations between YBT scores and knee moments during single-leg jump-landing would suggest that the simple-to-administer YBT could be used as a screening tool to infer knee moments during single-leg jump-landing. Coaches could administer this throughout a season and if changes in reach distances are observed from the baseline measurements, then that would warrant further investigations of the knee loading profiles of netballers via 3D motion analysis. From the results, a strong positive correlation was found between PKF moments and posteromedial reach distance; a moderate negative correlation was found between PKIR moments and anterior reach distance; whereas no association between PKV with any reach directions was found.

Higher PKF moment during single leg landing of the non-dominant leg was associated with increased posteromedial reach on the YBT. This finding is contradictory to previous studies that suggest further reaches in the YBT to be associated with decreased lower limb injury risk.18,19 To better understand this relationship, the mechanics involved with performing the posteromedial reach has to be discussed. Greater knee flexion is required to reach further in all directions of the YBT.33 As the body is lowered to reach further in the posteromedial direction, greater

![Figure 3. Moments and reach distances. a) flexor moment and posteromedial reach, b) internal rotation moment and anterior reach](image-url)
e eccentric contraction of the knee extensors/quadriceps, particularly the rectus femoris and vastus medialis, is required. This results in higher internal extensor moments, or, by inference, externally applied flexor moments. Knee flexor strength has also been reported to positively correlate with posteromedial reach distance. Maintaining postural stability during single-leg stance while reaching for distances using the contralateral leg requires co-contraction of both the knee flexors and extensors of the stance leg. How is this related to single-leg jump-landing mechanics?

Single-leg jump-landing requires co-contraction of the knee flexors and extensors in a similar manner as reaching for distances in the YBT for the maintenance of postural stability. To maintain balance when landing on one leg, the knee extensors and flexors contract eccentrically. These muscle activation patterns are similar when lowering oneself in unilateral stance to reach maximally with the contralateral leg during the YBT. Thus, internal knee extensor moments via quadriceps activation during single-leg jump-landing likely has implications on ACL strain.

Quadriceps activation during concentric knee extension causes anterior tibial translation, which can strain the ACL at knee flexion angles of less than 40°. Podraza & White, however, reported that the accompaniment of increased internal knee extensor moments via eccentric quadriceps activation with increased knee flexion angles on landing was a strategy for better energy absorption at impact; another study showed post-ACL-reconstruction participants displayed decreased peak knee internal extensor moment with reduced peak knee flexion angles in their affected knee compared to their contralateral uninjured knee. Hewett and colleagues reported that healthy participants performing a drop vertical jump displayed a positive correlation between maximal knee flexion angle with peak vertical ground reaction force. Prolonged energy absorption during landing reduces ACL strain as long as it is close to or within 40-50° knee flexion even if it results in higher internal knee extensor moments or peak vertical ground reaction force.

Participants in this study landed with an average of 39° knee flexion that is close to the 40-50° range. Consequently, the positive correlation between the posteromedial reach distances on the YBT and externally applied PKF moments during single leg landing could represent the similar mechanics involved for the maintenance of postural stability. While speculative, posteromedial reach distances on the YBT could be used to infer PKF moments during single leg landing; however, the additional knowledge of an individual's landing knee flexion angle would paint a clearer picture as to whether these moments indicate a safer or more dangerous landing pattern.

Decreased PKIR moments were associated with further reach ability in the anterior direction. Further anterior reach requires greater vastus medialis activation and knee flexor strength of the stance leg. While vastus medialis contraction coupled with the natural structural mechanism of a bending knee can internally rotate the tibia, sufficiently strong biceps femoris; a knee flexor; can counteract this internal rotation of the tibia, especially during landing. Activation of the biceps femoris plays an important role in resisting knee internal rotation caused by large eccentric quadriceps contraction during weight-acceptance phase of single-leg jump-landing. The neuromuscular parameters that enabled the participants to reach further anteriorly in the YBT without losing their stability could have also contributed in the decreased knee internal rotation moments during forward single-leg jump-landing. This is positive from an injury prevention perspective as the combination of both translation and rotation can significantly strain the ACL. While further research comprising a larger number of participants should be performed to confirm this relationship between anterior reach and externally applied PKIR, the current findings suggest that the anterior reach on the YBT could potentially serve as a simple-to-administer proxy to performing 3D motion analyses during single-leg jump-landing to gain an insight on PKIR moments; a contributor to ACL strain.

No correlation was found between PKV moments and YBT scores. This finding may not be surprising considering that the forward single-leg jump-landing is predominantly a sagittal plane movement. Lateral and diagonal jump landings have been shown to increase frontal plane knee loading significantly more than forward jump landings. Other studies have also found increased knee valgus angles and
moments when landing in the following conditions: 1) with perturbations during landing (e.g. avoiding a defender); 47 and 2) landing from high-velocity activities (e.g. running into a take-off before landing). 48 The current research does not comprise any of the abovementioned conditions; more relationships may surface if these were included.

Although the YBT has been linked with lower extremity injury risk, no research has investigated the relationship between scores on the YBT with knee moments during single-leg jump-landing to the researchers' knowledge. 18,19,49,50 It should be noted, though, that compensatory mechanisms following injuries, tightness and/or weakness of muscles and/or joint structures about the hip, knee and ankles may result in different movement patterns displayed in order to reach far. 15,23 Assessment of lower limb injury status and physical condition prior to testing on the YBT should be conducted to identify any pathomechanical confounders. If it is indeed possible to reach far with postures that put the joints at risk of injury, that would raise more questions as to what exactly the YBT assesses in terms of injury risk as well as the relationship between scores on the YBT and knee joint moments during single-leg jump-landing.

Limitations
Firstly, unlike single-leg jump-landing, the YBT does not involve rapid weight-acceptance. The single-leg jump-landing involves the ability to counteract externally applied moments while YBT execution involves the ability to generate internally applied moments. Secondly, the movement task in this study was limited to only the forward single leg jump for maximal distance, which is one of several movements performed within team sports that exacerbates non-contact ACL injury. Inclusion of more variations of such movements may provide more information of the risks of these other frequently performed moves. Lastly, the sample population in this study comprised national team netballers, which, while targeted, represents only a small population of team sport athletes and not ranging across various skill levels.

Future Research
Future research exploring performing the YBT reach as quickly as possible may better tease out the lower extremity's neuromuscular ability to decelerate a quickly lowering center of mass similar to a single-leg jump-landing, and potentially find additional correlations with the forward single-leg jump-landing. Further exploration of knee moments during lateral jump landings, with perturbations and at high velocities with the different YBT reach directions may provide a better idea of how PKV moments can be inferred through the YBT. In order to make more definitive conclusions from the findings from this study, further research should also be conducted on a larger number of participants in order to see if the results can be replicated to other sports and the general population. Additionally, a follow up on the incidences of non-contact ACL injuries post-test could provide a direct indication of the significance of the results from this study.

CONCLUSIONS
This study provides insights into the relationship between individual reach scores in the various directions of the YBT and externally applied knee moments (PKF, PKV and PKIR) of the non-dominant leg during the weight-acceptance phase of a forward single-leg jump-landing for maximal distance; a movement performed in netball and associated with non-contact ACL injuries. The positive correlation between posteromedial reach and PKF moments, and negative correlation between anterior reach and PKIR moments suggest that results on these simple-to-perform lower limb reach tests could potentially be used to infer knee moments that have been reported to contribute to non-contact ACL injuries during single-leg jump-landing on the non-dominant leg. Additional information on landing mechanics, such as maximal knee flexion angles, would provide further insight on whether increased knee flexor moments pose higher injury angles to the ACL during single-leg jump-landing. With its ease of use, the YBT can be implemented regularly to monitor an athletes' scores compared with his/her baseline measurements. Significant changes in the reach distances from baseline measurements could serve as 'alarms' for further investigations into the knee loading profiles of netballers during single leg landing via 3D motion analysis; the current gold standard but a time-consuming process; from a knee injury prevention perspective.
REFERENCES


ABSTRACT

Background: In contrast to static stretching (SS), previous research has demonstrated increases in flexibility after an acute bout of self-myofascial release (SMR) without any subsequent decreases in force output. Previous research has utilized measures of surface electromyography (sEMG) and mechanomyography (MMG) to examine the influence of SS on the electrical and mechanical processes of muscle activation, respectively. However, there is a lack of research examining the potential changes in electro-mechanical muscle activation post-SMR.

Purpose: To examine the influence of SMR, via an acute bout of foam rolling (FR) to the vastus lateralis (VL), on the expression of knee extension force output and the inter-muscular electro-mechanical activation of the quadriceps musculature.

Study Design: Randomized crossover trial.

Methods: Twenty (10 males, 10 females) recreationally-active participants with prior FR experience completed both SMR and control (CON) testing protocols during separate testing sessions that were conducted in a randomized order 48 hours apart. During the SMR protocol, participants performed 3 sets of 60 seconds of FR over the VL portion of their quadriceps musculature, with 60 seconds of rest between sets. During the CON protocol, participants quietly sat upright for 10 minutes. Peak knee extension force output \( (\text{Force}_{\text{peak}}) \) data, as well as sEMG and MMG data from the VL and the rectus femoris (RF) were collected during maximal voluntary isometric contractions (MVICs) before and after both testing protocols. Root mean square sEMG and MMG amplitudes were calculated to represent electro-mechanical muscle activation of the VL \( (\text{VL–sEMG}_{\text{RMS}}, \text{VL–MMG}_{\text{RMS}}) \) and RF \( (\text{RF–sEMG}_{\text{RMS}}, \text{RF–MMG}_{\text{RMS}}) \) musculature.

Results: Repeated measures analyses of variance (RM ANOVAs) identified a significant \( (p < 0.05) \) increase in \( \text{Force}_{\text{peak}} \) within the SMR protocol among males, but no change among females. No statistically significant changes in any electro-mechanical muscle activation measures were identified pre-to-post-SMR within either sex.

Conclusion: In contrast to the SS literature body, these results suggest that SMR does not influence the electro-mechanical aspects of muscle activation during MVICs. These results provide support for the absence of decreases in force output post-SMR, but further examination regarding the potential muscle mass influence of SMR on electro-mechanical muscle function remains warranted.

Level of Evidence: 2c

Keywords: electro-mechanical efficiency, foam rolling, mechanomyography, surface electromyography

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INTRODUCTION

Self-myofascial release (SMR), applied via foam rolling (FR), is commonly utilized by individuals as a method of increasing joint range of motion (ROM).1-3 The prescription of SMR has also grown in popularity among practitioners,4-5 with 81% of allied health professionals utilizing FR within their practice.6 One of the potential factors associated with the increased utilization of SMR has been the fact that previous research has demonstrated increases in joint ROM after an acute bout of SMR, theoretically due to an increase in muscle tissue extensibility, without any subsequent decreases in force output.7-9 The lack of influence on force output after SMR-related increases in joint ROM also differs from the static stretching (SS) literature, which has routinely demonstrated a decrease in force and power output after an acute bout of SS.10-12 As such, an emerging body of evidence suggests that practitioners can prescribe SMR interventions without detrimentally influencing subsequent athletic performance.13

The physiological mechanisms in which SS and SMR influence muscle tissue extensibility have been largely associated with either neural and/or morphological mechanisms. Specifically, potential neural mechanisms of both SS14 and SMR1 include activation of Golgi tendon organs (GTOs) and/or mechanoreceptors (e.g., group III/IV afferents), which decrease the efferent α-motorneuron drive, creating a relaxation effect on the target musculature and an increase in muscle tissue extensibility. Potential morphological mechanisms of SS include changes in viscoelastic properties of the muscle-tendon unit (MTU), thereby increasing the compliance of the MTU, and the subsequent extensibility of the target musculature.15 Since these mechanisms may also inhibit the neural activation and viscoelastic properties of the target musculature, these are often the mechanisms used to describe the decrease in force-generating capacity of the musculature after SS.16 In contrast, potential morphological mechanisms of SMR include a reduction in fascial adhesions and changes in fluid mechanics of the fascia surrounding the target musculature due to a thixotropy-like effect17-18 rendering the fascia more malleable and increasing the extensibility of the target musculature.1 While these may be slightly different mechanisms from those for SS, these processes theoretically influence the viscoelastic properties of the fascia, and in turn, increase the pliability of the muscle tissue resulting in increased muscle extensibility.

Unlike the SMR literature body, previous SS research has utilized non-invasive methodologies to examine both the neural and mechanical properties of muscle function pre- and post-SS. Specifically, surface electromyographic (sEMG) measures, which represent the electrical processes of muscle activation, and mechanomyographic (MMG) measures, which represent the mechanical processes of muscle activation, have been simultaneously collected to assess electro-mechanical muscle function in a variety of capacities,19-22 including to examine potential changes as a result of SS.21-26 For example, previous research has demonstrated a decrease in sEMG amplitude,27-29 but an increase in MMG amplitude,25 during isometric muscle actions after an acute bout of SS. These results suggest that SS is capable of creating both electrical and mechanical changes in muscle function, providing evidence to the previously described neural and morphological alterations that theoretically occur as a result of SS.14-16

In contrast to the SS literature body, there is a lack of research examining the potential changes in electro-mechanical function as a result of SMR. Currently, there are equivocal findings in the literature regarding the influence of SMR on sEMG activity, with previous research demonstrating a decrease in sEMG measures post-SMR,30-31 as well as no changes in sEMG measures post-SMR.7-9,32-33 These conflicting results could be due to changes in inter-muscular activation post-SMR, as Cavanaugh et al.31 demonstrated a significant decrease in sEMG measures of the hamstrings after FR was applied to the quadriceps musculature, but further investigation of potential muscle coordination changes is still required. In addition, the influence of SMR on MMG measures has yet to be examined and no previous research has simultaneously collected both sEMG and MMG measures. Thus, the examination of the influence of SMR on the mechanical aspects of electro-mechanical muscle function remain largely unexplored. Furthermore, previous research has also suggested that MMG signal may be particularly sensitive to the tissue stiffness of the vastus lateralis given the
longitudinal covering of the iliotibial band along this aspect of the quadriceps musculature. Therefore, the purpose of this study was to examine the influence of SMR, via an acute bout of FR to the vastus lateralis (VL), on the expression of knee extension force output and the inter-muscular electro-mechanical activation of the quadriceps musculature.

METHODS

Participants
Twenty (10 males, 10 females) recreationally-active participants with prior FR experience volunteered to participate in the current study (mean ± SD, age: 24.2 ± 2.6 yrs; height: 173.1 ± 9.4 cm; body mass: 70.7 ± 17.6 kg). This study was approved by the Institutional Review Board at the University of Wisconsin-Milwaukee. Before any data were collected, all participants provided written informed consent to the study protocols. The functionally dominant leg of each participant was determined based upon the leg in which the participant would prefer to kick a ball in order to achieve maximal distance.

Testing Protocols
To ensure a relative similar starting point in terms of blood flow and tissue warmth, all participants first completed a 5-minute warm-up on a bicycle ergometer (Ergomedic 828E, Monark Exercise AB, Vansbro, Sweden), at 0.5 kp of resistance and a cadence of 50 rpm, at the beginning of each testing period. Each participant completed both the SMR and control (CON) testing protocols (i.e., crossover design). Testing protocols were completed in a research laboratory 48 hours apart during separate testing sessions. Participants were instructed to not perform any resistance training and/or vigorous physical activity or exercise in-between testing sessions. Beyond instructing the participants to perform the FR in a slow and controlled manner, the speed of the FR was not regulated for by the researchers.

CON Protocol
During the CON protocol, participants were instructed to quietly sit upright for 10 minutes. Participants were not allowed to walk, stand up, or stretch during this period.

Maximal Voluntary Isometric Contractions
Pre- and post- each testing protocol, participants performed five maximal isometric voluntary contractions (MVICs) of knee extension consistent with standard manual muscle testing techniques and according to muscle testing protocols previously utilized in the literature. Specifically, the dominant leg of each participant was secured to a treatment table at 60° of knee flexion and 90° of concurrent hip flexion (Figure 2). Participants were instructed to sit upright with their arms across their chest and to maintain each MVIC of knee extension for five seconds. Verbal encouragement during each MVIC, as well as 60 seconds of rest between each MVIC, were provided by the researchers.

Knee Extension Force Data
The expression of peak knee extension force output (kg) during each MVIC was measured using a handheld dynamometer (MicroFET 2, Hoggan Health Industries, Salt Lake City, UT) that was secured with an immovable strap (Figure 2). The handheld dynamometer was placed on the anterior aspect of the tibia and just proximal to the malleoli of the dominant leg of each participant. Previous research has reported adequate validity ($r = 0.894$), as well as
excellent intrasession (ICCs = 0.82–0.93) and good-
to-excellent intersession (ICCs = 0.70–0.92) test-
retest reliability, of the assessment of peak knee extension force via handheld dynamometry. Only force data from the MVIC resulting in the greatest peak knee extension muscular force output \( (\text{Force}_{\text{peak}}) \) for each participant were used in all subsequent data processing and statistical analyses.

Electro-Mechanical Muscle Activation Data

All electro-mechanical muscle activation data (i.e., sEMG, MMG, & EME) were collected, and are subsequently reported, according to commonly utilized sEMG and MMG standards. Specifically, sEMG and MMG data were collected from the VL and rectus femoris (RF) musculature associated with quadriceps of the dominant leg of each participant. All sEMG and MMG signals were collected using the Noraxon Telemyo 2G System at a sampling frequency of 1,500 Hz and processed and analyzed using MyoResearch XP software (Noraxon U.S.A., Inc., Scottsdale, AZ). Only electro-mechanical muscle activation data from the \( \text{Force}_{\text{peak}} \) MVIC for each participant were used in all subsequent signal processing and statistical analyses.

sEMG Data

All sEMG data were collected using bipolar Ag/AgCl surface electrodes (MeshTrode A10040-60, Vermed, Buffalo, NY) placed along the longitudinal axis of the VL and RF quadriceps muscle bellies, with the reference electrode placed over the patella of each participant. To reduce any impedance of the sEMG signals, the skin of each participant was first shaved with a disposable razor and abraded using isopropyl alcohol and sterile gauze before electrode placement. All sEMG data were differentially amplified (gain = 2000×) and digitally bandpass filtered (fourth-order Butterworth) at 10–500 Hz. Root mean square amplitudes (μV) were calculated from sEMG signals collected from the VL (VL–sEMGRMS) and RF (RF–sEMGRMS) musculature using a smoothing window of 50 milliseconds during three second epochs corresponding to seconds 1.0–4.0 of the five-second knee extension MVIC. Black permanent marker was used to outline electrode placement to ensure the same electrode placement during both SMR and CON protocols. Previous research has demonstrated excellent intrasession test-retest reliability of sEMGRMS data collected during MVICs from the quadriceps musculature (ICCs = 0.95–0.97), as well as good intersession test-retest reliability of sEMG amplitude data collected during MVICs in general (ICCs = 0.68–0.74) (Yang & Winter, 1983). In addition, previous research within both the SS and SMR literature bodies have examined sEMG data in a similar manner.

MMG Data

All MMG data were collected using tri-axial piezoelectric accelerometers (352A24, PCB Piezotronics,
Depew, NY). Each accelerometer (dimensions = 0.5 cm × 0.5 cm × 1.0 cm; sensitivity = 100 mV/g) was placed between the previously placed proximal and distal bipolar sEMG electrodes using double-sided adhesive tape, resulting in an inter-electrode distance of 2.5 cm between sEMG electrodes (Figure 3). All MMG data were digitally bandpass filtered at 5–150 Hz. Similar to the sEMG signals, root mean square amplitudes (mV²) were calculated from MMG signals collected from the VL (VL–MMG RMS) and RF (RF–MMG RMS) musculature using a smoothing window of 50 milliseconds during three second epochs corresponding to seconds 1.0–4.0 of the 5-second knee extension MVIC. Previous research has demonstrated excellent intrasession test-retest reliability (ICCs = 0.84–0.96) and excellent intersession test-retest reliability (ICC = 0.81) of MMG RMS data collected during MVICs from the quadriceps musculature, as well as among MMG RMS data collected during MVICs in general (ICCs = 0.94–0.97). In addition, previous research within the SS literature body has examined MMG data in a similar manner.

Statistical Analyses

All statistical analyses were conducted using the IBM SPSS 25 software package (IBM Corp., Armonk, NY). An alpha of $p < 0.05$ determined statistical significance for all analyses. Previous research has demonstrated differences in both electrical and mechanical muscle function between sexes during MVICs. In particular, differences in MMG RMS data have been attributed to potential differences in muscle stiffness between males and females due to sex differences in muscle mass. Due to this, independent t-tests were first conducted to identify potential differences in Forcepeak, VL–sEMG RMS, RF–sEMG RMS, VL–MMG RMS, and RF–MMG RMS measures at baseline between sexes. Since statistically significant differences were identified within all measures (Table 1), all subsequent statistical analyses were split by sex.

In order to examine the potential influence of an acute bout of SMR on the expression of knee extension force output and the electro-mechanical activation of the VL and RF quadriceps musculature, separate 2 × 2 (protocol × time) within-between repeated measure analyses of variance (RM ANOVAs) and follow-up main effects were conducted for each measure of interest: Forcepeak, VL–sEMG RMS, RF–sEMG RMS, VL–MMG RMS, and RF–MMG RMS. In addition, if significant differences in any measure were identified, the analysis was repeated with body mass included as a covariate in order to identify the potential influence of muscle mass on that measure of interest.

### Table 1. Baseline sex differences in participant characteristics and measures of interest (data presented as mean ± SE).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>24.20 ± 0.71</td>
<td>24.10 ± 0.95</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180.33 ± 2.22*</td>
<td>165.80 ± 1.54</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>82.08 ± 4.96*</td>
<td>59.30 ± 3.71</td>
</tr>
<tr>
<td>Forcepeak (kg)</td>
<td>33.94 ± 2.86*</td>
<td>21.61 ± 1.01</td>
</tr>
<tr>
<td>VL–sEMG RMS (µV)</td>
<td>371.57 ± 72.22*</td>
<td>180.24 ± 26.51</td>
</tr>
<tr>
<td>RF–sEMG RMS (µV)</td>
<td>205.67 ± 22.30*</td>
<td>113.02 ± 13.37</td>
</tr>
<tr>
<td>VL–MMG RMS (mV²)</td>
<td>0.42 ± 0.04*</td>
<td>0.32 ± 0.04</td>
</tr>
<tr>
<td>RF–MMG RMS (mV²)</td>
<td>0.59 ± 0.06*</td>
<td>0.56 ± 0.03</td>
</tr>
</tbody>
</table>

*Forcepeak = peak knee extension force output; VL = vastus lateralis musculature; RF = rectus femoris musculature; sEMG RMS = root mean square amplitude of the surface electromyographic data; MMG RMS = root mean square amplitude of the mechanomyographic data. *Males significantly greater than Females ($p < 0.05$)
Finally, standardized effect size statistics were calculated to determine potential practical pre-to-post changes in the expression of knee extension force output and the electro-mechanical activation of the VL and RF quadriceps musculature. Given the small sample size, Hedge’s $g$ effect size statistics were chosen\(^\text{67}\) and were interpreted using the following criteria\(^\text{58}\): trivial (\(g \leq 0.19\)), small (\(0.20 \leq g \leq 0.49\)), medium (\(0.50 \leq g \leq 0.79\)), large (\(0.80 \leq g \leq 1.29\)), and very large (\(1.30 \leq g\)).

**RESULTS**

Descriptive statistics (mean ± SE) within sexes are reported in Table 2 for all measures of knee extension force output and electro-mechanical muscle activation collected during each testing protocol (i.e., SMR & CON).

**Force\(_{\text{peak}}\) Data**

Among males, no significant protocol × time interaction effect on Force\(_{\text{peak}}\) was identified (\(F_{1,18} = 1.577, p = 0.225\)). Although a significant and small main effect of time on Force\(_{\text{peak}}\) was identified within the SMR protocol (\(p = 0.039, g = 0.24\), when body mass was controlled for, no significant effect of time was identified within either the SMR (\(p = 0.920\)) or CON (\(p = 0.518\)) protocols. A non-significant and trivial main effect of time on Force\(_{\text{peak}}\) was identified within the CON protocol (\(p = 0.468, g = 0.07\)). Among females, no significant protocol × time interaction effect on Force\(_{\text{peak}}\) was identified (\(F_{1,18} = 1.630, p = 0.218\)). In addition, non-significant and trivial main effects of time on Force\(_{\text{peak}}\) were identified within both the SMR (\(p = 0.530, g = 0.11\)) and CON (\(p = 0.170, g = 0.13\)) protocols. Collectively, these results suggest that the SMR protocol significantly influenced the Force\(_{\text{peak}}\) data among males, and that SMR may influence Force\(_{\text{peak}}\) via muscle mass, as this influence was no longer statistically significant when body mass was controlled for as a covariate. In addition, the effect of SMR on Force\(_{\text{peak}}\) was small, and did not create a change that was significantly different between the SMR and CON.

**Table 2. Influence of an acute bout of SMR on the expression of knee extension force output and electro-mechanical muscle activation.**

<table>
<thead>
<tr>
<th>Measure</th>
<th>SMR</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre (mean ± SE)</td>
<td>Post (mean ± SE)</td>
<td>Significance</td>
</tr>
<tr>
<td><strong>Males (n = 10)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force(_{\text{peak}}) (kg)</td>
<td>34.2 ± 3.7</td>
<td>37.6 ± 4.7</td>
</tr>
<tr>
<td>VL-\SEMG(_{\text{SMR}}) ((\mu)V)</td>
<td>370.5 ± 103.4</td>
<td>345.1 ± 86.0</td>
</tr>
<tr>
<td>RF-\SEMG(_{\text{SMR}}) ((\mu)V)</td>
<td>207.0 ± 29.0</td>
<td>190.3 ± 28.0</td>
</tr>
<tr>
<td>VL-M\MMG(_{\text{SMR}}) ((\text{mV}^2))</td>
<td>0.4 ± 0.1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>RF-M\MMG(_{\text{SMR}}) ((\text{mV}^2))</td>
<td>0.6 ± 0.1</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td><strong>Females (n = 10)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force(_{\text{peak}}) (kg)</td>
<td>21.7 ± 1.3</td>
<td>21.1 ± 1.8</td>
</tr>
<tr>
<td>VL-\SEMG(_{\text{SMR}}) ((\mu)V)</td>
<td>189.6 ± 44.8</td>
<td>174.1 ± 40.3</td>
</tr>
<tr>
<td>RF-\SEMG(_{\text{SMR}}) ((\mu)V)</td>
<td>116.5 ± 21.0</td>
<td>112.6 ± 18.5</td>
</tr>
<tr>
<td>VL-M\MMG(_{\text{SMR}}) ((\text{mV}^2))</td>
<td>0.3 ± 0.1</td>
<td>0.32 ± 0.1</td>
</tr>
<tr>
<td>RF-M\MMG(_{\text{SMR}}) ((\text{mV}^2))</td>
<td>0.4 ± 0.1</td>
<td>0.35 ± 0.04</td>
</tr>
</tbody>
</table>

SMR = self-myofascial release protocol; CON = control protocol; Force\(_{\text{peak}}\) = peak knee extension force output; VL = vastus lateralis musculature; RF = rectus femoris musculature; \SEMG\(_{\text{SMR}}\) = root mean square amplitude of the surface electromyographic data; M\MMG\(_{\text{SMR}}\) = root mean square amplitude of the mechanomyographic data.

\(^{a}\)Effect size interpretations are based on guidelines provided by Sullivan and Feinn\(^\text{58}\).
protocols. Finally, neither the SMR and CON protocols significantly influenced Forcepeak data among females (Table 2).

### sEMG Data

Among males, no significant protocol × time interaction effects on VL–sEMG RMS ($F_{1,18} = 0.116, p = 0.737$) and RF–sEMG RMS ($F_{1,18} = 0.448, p = 0.512$) were identified. In addition, non-significant and trivial main effects of time on VL–sEMG RMS and RF–sEMG RMS were identified within both the SMR ($p = 0.480, g = 0.08; p = 0.378, g = 0.18$, respectively) and CON ($p = 0.513, g = 0.04; p = 0.761, g = 0.03$, respectively) protocols. Among females, no significant protocol × time interaction effects on VL–sEMG RMS ($F_{1,18} = 1.698, p = 0.209$) and RF–sEMG RMS ($F_{1,18} = 1.138, p = 0.300$) were identified. In addition, non-significant and trivial main effects of time on VL–sEMG RMS and RF–sEMG RMS were identified within both the SMR ($p = 0.420, g = 0.11; p = 0.597, g = 0.06$, respectively) and CON ($p = 0.161, g = 0.10; p = 0.283, g = 0.08$, respectively) protocols. Collectively, these results suggest that the SMR and CON protocols did not significantly influence the VL–sEMG RMS and RF–sEMG RMS data among both males and females (Table 2).

### MMG Data

Among males, no significant protocol × time interaction effects on VL–MMG RMS ($F_{1,18} = 0.432, p = 0.519$) and RF–MMG RMS ($F_{1,18} = 0.174, p = 0.681$) were identified. In addition, non-significant and trivial-to-small main effects of time on VL–MMG RMS and RF–MMG RMS were identified within both the SMR ($p = 0.939, g < 0.01; p = 0.215, g = 0.33$, respectively) and CON ($p = 0.226, g = 0.17; p = 0.578, g = 0.13$, respectively) protocols. Among females, no significant protocol × time interaction effects on VL–MMG RMS ($F_{1,18} = 0.145, p = 0.707$) and RF–MMG RMS ($F_{1,18} = 0.010, p = 0.932$) were identified. In addition, non-significant and trivial main effects of time on VL–MMG RMS and RF–MMG RMS were identified within both the SMR ($p = 0.689, g = 0.08; p = 0.896, g = 0.07$, respectively) and CON ($p = 0.912, g = 0.10; p = 0.914, g < 0.01$, respectively) protocols. Collectively, these results suggest that the SMR and CON protocols did not significantly influence the VL–MMG RMS and RF–MMG RMS data among both males and females (Table 2).

### DISCUSSION

The purpose of this study was to examine the influence of SMR, via an acute bout of FR to the VL, on the expression of knee extension force output and the inter-muscular electro-mechanical activation of the quadriceps musculature. The results of the current study suggest that SMR may result in a small, but significant increases in knee extension Forcepeak among males, but no significant change in Forcepeak within the SMR group was identified among females. This potential sex-specific influence on the expression of knee extension force output may be due to differences in muscle mass between males and females, as no significant changes in Forcepeak were identified among males after controlling for body mass. However, although this pre-to-post change in Forcepeak was significant with the SMR group, the post-Forcepeak within the SMR group was not significantly different from the post-Forcepeak within the CON group. These findings differ with the existing body of literature indicating a lack of influence of SMR on the expression of force output. Nevertheless, due to the resulting increase in force production (vs. decrease), these findings still provide further support for the use of SMR, instead of SS, as a method of increasing joint ROM without any subsequent decrements in force production that may hinder sport performance.

Similarly, the results of the current study also indicate that SMR does not influence the electrical processes associated with the electro-mechanical activation of the quadriceps musculature, as significant changes in sEMG RMS amplitudes were not identified within either sex. Given the fact that a decrease in the efferent α-motoneuron drive due to activation of Golgi tendon organs (GTOs) and/or mechanoreceptors (e.g., group III/IV afferents) have been proposed as neural mechanisms of increasing muscle tissue flexibility via SMR, it is surprising that decreases in sEMG RMS amplitudes were not identified in the current study. These results are further surprising given the fact that an increase in Forcepeak was identified among males, which suggests that this increase in force output was not attributed to the electrical aspects of muscle activation. That said, these results further contribute to the body literature that has previously identified no changes in
sEMG measures post-SMR\textsuperscript{7-9,32-33} as well as decreases in sEMG measures post-SMR\textsuperscript{30-31}

It has been hypothesized that these conflicting results in the previous literature could be due to changes in inter-muscular activation, as significant decreases in sEMG measures of the hamstring musculature has been observed in the literature after SMR was applied to the quadriceps musculature.\textsuperscript{31} However, even though the SMR was applied specifically to the VL musculature in the current study, no changes in the RF–sEMG\textsubscript{RMS} data were identified, and Killen et al.\textsuperscript{32} did not identify post-SMR changes in sEMG measures of the contralateral musculature as well. Therefore, it is possible that SMR only creates electrical changes in electro-mechanical muscle activation within the antagonist musculature (vs. the agonist or contralateral musculature). These changes could be due to reciprocal inhibition of the antagonist musculature (i.e., hamstrings) as a result of the SMR applied to the agonist musculature (i.e., quadriceps), which is a phenomenon that has been demonstrated after both SS and proprioceptive neuromuscular facilitation (PNF) stretching.\textsuperscript{59} In addition, both studies that have previously identified significant decreases in sEMG measures post-SMR examined muscle activity during dynamic muscle contractions, such as a lunge\textsuperscript{30} and a single-leg landing from a hurdle jump\textsuperscript{31} whereas the current study utilized an isometric contraction. Since this is the first study to simultaneously examine the influence of SMR on both the electrical and mechanical processes associated with muscle activation, an isometric contraction was chosen to better isolate the potential influence of SMR on these parameters be removing the influence of motion artifact that is associated with dynamic muscle contractions. That said, it is possible that the influence of SMR on the electrical processes associated with the electro-mechanical muscle activation is also specific to the type of muscle action.

In concurrence with the lack of change in the electrical processes associated with muscle activation, the results of the current study indicate that SMR does not influence the mechanical processes associated with activation of the quadriceps musculature either, as significant changes in MMG\textsubscript{RMS} amplitudes were also not identified. While this was the first known study to examine the influence of SMR on measures of MMG, previous research has identified increases in MMG amplitude post-SS.\textsuperscript{25} Since it has been suggested that MMG amplitude may be inversely related to muscle stiffness,\textsuperscript{19,34} the previously identified increases in MMG amplitude post-SS have been attributed to the potential increase in compliance of the non-contractile tissues (i.e., a decrease in muscle stiffness), which in turn, may allow for greater lateral oscillations of the muscle fibers during contraction (i.e., increase in MMG amplitude). Therefore, given the fact that adaptations to the viscoelastic properties of the fascia have been proposed as morphological mechanisms of increasing muscle tissue flexibility via SMR,\textsuperscript{1} it is surprising that changes in MMG\textsubscript{RMS} amplitudes were not identified in the current study.

When taken together, the results of the current study indicate that SMR does not influence the electro-mechanical aspects of quadriceps muscle activation, which provides further mechanistic rationale regarding the maintenance in force output post-SMR. However, these results suggest that although previous research has routinely demonstrated that SMR has the ability to increase muscle tissue flexibility,\textsuperscript{1-3} the physiological mechanisms in which this increase in muscle tissue flexibility are achieved remain unclear. Although the lack of change in MMG\textsubscript{RMS} amplitude suggests these mechanisms do not influence the mechanical aspects of muscle activation, changes in fluid mechanics of the fascia surrounding the target musculature due to the previously described thixotropy-like effect\textsuperscript{17-18} remain possible. For example, recent research has suggested that increases in arterial blood flow,\textsuperscript{60} potentially due to increases in nitric oxide, and subsequent changes in endothelial function,\textsuperscript{61} are created after an acute bout of FR. These potential physiological changes may ultimately render the fascia more malleable and the increase the extensibility of the target musculature, but in a manner that does not influence the electrical or mechanical aspects of muscle activation. Furthermore, such changes may be responsible for the potential sex-specific changes in Force\textsubscript{peak} observed in the current study. As such, future research should utilize other methodologies (e.g., diagnostic ultrasound, heart rate variability, etc.) to further investigate potential
changes in physiological processes, both local and systemic, that occur as a result of SMR.

However, it should be noted that the current study only examined the influence of SMR on electromechanical muscle activation during isometric muscle actions at one joint position (60° of knee flexion). It is possible that SMR may influence the mechanical processes associated with electromechanical muscle activation (i.e., MMG measures) during isometric muscle actions differently based on joint position, which is a phenomenon that has been previously observed within the SS literature body. In addition, based on the previously identified discrepancies in the literature regarding post-SMR changes in sEMG measures between isometric and dynamic muscle actions, it is possible that post-SMR changes in MMG measures may also differ between isometric and dynamic muscle contractions. Furthermore, the influence of SMR on electromechanical muscle activation may be specific to muscle action type (i.e., concentric vs. eccentric) as well. While this has yet to be examined in the SMR literature, the SS literature body has demonstrated significant increases in MMG amplitude, as well as no changes in MMG amplitude, during isokinetic muscle actions post-SS. Such conflicting results in the SS literature have not only been attributed to differences between muscle actions types, but could be due to inherent differences in muscle architecture as well. For example, Herda et al. proposed that the post-SS observed increases in MMG amplitude during concentric knee flexion muscle actions, and the lack of change in MMG amplitude during concentric knee extension muscle actions, may be related to the fusiform nature of the hamstring musculature (vs. the pennate nature of the quadriceps musculature). As a result, SS may have a greater influence on MTU compliance, and thus, a greater influence on measures of MMG, within muscles comprised of a fusiform architecture (e.g., hamstrings, biceps brachi, etc.) in comparison to muscles comprised of a pennate architecture (e.g., quadriceps, deltoid, etc.). Therefore, it is also possible that differences in muscle architecture influence the underlying mechanisms in which SMR creates changes in muscle flexibility. In contrast, given the influence of muscle mass on force output, it is possible that muscle mass may mediate the influence of SMR on the physiological processes of electromechanical function. Such influence may also explain the potential sex-specific changes in Forcepeak observed in the current study. Thus, further research examining potential changes in both sEMG measures and MMG measures at a variety of joint angles, during various muscle actions, within different muscle architecture types, while controlling for sex differences in muscle mass is warranted.

Thus, it is also possible that the type of foam roller and the duration of FR may influence the acute physiological adaptations associated with SMR. Although the body of literature is currently limited, research suggests that different types of foam rollers exert differing level of pressure to the target musculature. In addition, recent research also suggests that vibrating foam rollers may create differing (or enhanced) effects than non-vibrating foam rollers. Furthermore, a recent commentary on the state of the SMR literature has highlighted the fact that there appear to be a large variety in FR methods, including FR durations, examined in the SMR literature, which has also created a large variety in the SMR methodologies utilized by practitioners. It is possible that this large variety in SMR methodologies utilized by researchers has influenced the conflicting findings in the literature regarding the influence of SMR on the electrical aspects of electromechanical function. Notably, the duration in which FR is applied may create differing changes in subsequent electromechanical activation post-SMR. Thus, although the results of the current study did not identify an influence of SMR on subsequent electromechanical aspects of muscle activation, further examination on the influence of differing types and durations of SMR on electromechanical muscle activation remains warranted.

Several limitations of the current study should be acknowledged. First, the amount of force applied to the foam roller due to bodyweight was not controlled beyond researchers ensuring proper FR form. It is possible that subtle weight shifting across the participants could have resulted in differing amounts of relative force being applied to the foam roller, which could theoretically influence the SMR mechanisms. In addition, the speed of the FR was not controlled.
for by the researchers. However, recent research also suggests that the amount of force applied to the quadriceps musculature during FR did not influence the observed changes in ROM or result in differing MVICs pre-to-post-SMR\(^{67}\) and that the speed at which FR was conducted did not influence the observed changes in ROM or myofascial stiffness pre-to-post-SMR\(^{68}\). Thus, while the amount of force applied during FR, and the speed at which the FR was conducted, were not controlled across participants, this previous research suggests these methodological factors did not likely influence the results of the current study.

CONCLUSIONS
The results of the current study indicate that SMR does not influence the electro-mechanical aspects of quadriceps muscle activation. These results provide further mechanistic rationale regarding the lack of any subsequent decreases in force output observed in the current study, as well as previously identified in the literature. Therefore, clinicians and practitioners should recommend the use of SMR, instead of SS, as a method of increasing flexibility, due to a lack of decrements in force production that may acutely hinder sport performance. Given the potential for SMR-related changes in the expression of force to be mediated by body mass, it is also possible that clinicians may choose to utilize SMR (or SS) based on the size of the individual. However, further research examining the potential sex-specific and/or muscle mass influence of different SMR types and protocols on electro-mechanical muscle activation at a variety of joint angles, during various muscle actions, and within different muscle architecture types remains warranted.

REFERENCES


ABSTRACT

Background: Anterior cruciate ligament injuries are among the most common knee injuries. Mechanism of injury is classified as contact or non-contact. The majority of anterior cruciate ligament ruptures occur through a non-contact mechanism of injury. Non-contact anterior cruciate ligament ruptures are associated with biomechanical and neuromuscular risk factors that can predispose athletes to injuries and may impact future function. Non-contact mechanism of injury may be preceded by poor dynamic knee stability and therefore those with a non-contact mechanism of injury may be prone to poor dynamic knee stability post-operatively. Understanding how mechanism of injury affects post-operative functional recovery may have clinical implications on rehabilitation.

Purpose: The purpose of this study was to determine if mechanism of injury influenced strength, functional performance, patient-reported outcome measures, and psychological outlook in athletes at four time points in the first two years following anterior cruciate ligament reconstruction.

Study Design: Secondary analysis of a clinical trial.

Methods: Seventy-nine athletes underwent functional testing at enrollment after impairment resolution. Quadriceps strength, hop testing, and patient-reported outcome measures were evaluated post-operatively at enrollment, following return-to-sport training and one year and two years after anterior cruciate ligament reconstruction. Participants were dichotomized by mechanism of injury (29 contact, 50 noncontact). Independent t-tests were used to compare differences between groups.

Results: There were no meaningful differences between contact and non-contact mechanism of injury in any variables at enrollment, post-training, one year, or two years after anterior cruciate ligament reconstruction.

Conclusion: Function did not differ according to mechanism of injury during late stage rehabilitation or one or two years after anterior cruciate ligament reconstruction.

Level of Evidence: III

Keywords: anterior cruciate ligament, mechanism of injury, functional outcomes, movement system

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INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most common traumatic knee injuries.1 Mechanisms of ACL injuries are classified as direct contact to the knee or body, or non-contact.2–5 ACL injuries from direct contact occur when an external load (e.g., athlete or an object) precedes the ACL injury. Non-contact injuries occur without physical contact between athletes.4 The majority of ACL ruptures occur through a non-contact mechanism of injury (MOI), as opposed to a contact MOI.4,6–9 Non-contact ACL ruptures are primarily related to biomechanical and neuromuscular risk factors10–13 that can predispose athletes to initial injuries and have the potential to impact future function.14,15 After ACL rupture, reconstruction and rehabilitation, clinicians recommend athletes pass return to sport (RTS) criteria to reduce reinjury risk.16–19 Considering the neuromuscular deficits that often precede non-contact ACL injury, individuals who sustained a non-contact MOI may be predisposed to poor dynamic knee stability and neuromuscular deficits post-operatively. Further understanding how MOI might affect post-operative rehabilitation may have important clinical implications on functional recovery.

MOI may influence knee stability after acute ACL injury, with those sustaining non-contact ACL injuries, compared to contact ACL injuries, being more likely to be classified as noncopers.15 A noncoper is characterized by the inability to dynamically stabilize the knee after ACL injury, resulting in episodes of knee giving way.20 Those categorized as noncopers after ACL rupture demonstrate worse overall clinical presentation including decreased movement pattern quality, quadriceps strength, and poorer odds of long-term success.21–27 Although the exact etiology of non-contact injury remains unknown, video analyses during time of injury show most injuries occur with aberrant mechanics during change in direction, sudden deceleration, valgus collapse, or pivoting and cutting with the knee in a more extended position and a planted foot.3,8,13,28 Similarly, risk factors in non-contact injuries are often associated with poor neuromuscular control and coordination of the limb during an intended movement, for example, dynamic knee valgus and decreased muscle stiffness around the knee joint.12,29–32 Biomechanical deficits and poor neuromuscular control are prevalent in non-contact MOI. Athletes who demonstrate neuromuscular deficits preceding their injuries may potentially be predisposed to poor dynamic knee stability and function post-operatively.

It is unclear if athletes who sustained a non-contact mechanism of ACL injury, compared to athletes who sustain a contact mechanism of injury, differ in their functional outcomes following anterior cruciate ligament reconstruction (ACLR). The purpose of this study was to investigate the strength, functional performance, patient-reported outcome measures, and psychological outlook of athletes who sustained non-contact versus contact ACL injuries at four key time points within the first two years following ACLR. These time points were: after rehabilitation (enrollment), following RTS training, and at one and two years after ACLR. Considering the potential neuromuscular and biomechanical differences in those who sustain non-contact MOI, the hypothesis was that there would be differences in clinical and patient reported outcomes during rehabilitation based on MOI.

METHODS

This is a secondary analysis of prospectively collected data from a clinical trial (NCT01773317) approved by the University of Delaware Institutional Review Board. Athletes participated in this study between November 2011 and August 2018 at the University of Delaware. Participants provided written informed consent; additional consent and assent were obtained from parents/guardians and minors, and rights of the participants were protected.

Participants

Male and female athletes who sustained a primary ACL injury and underwent ACLR were recruited for the study. To enroll in the study, participants must have previously been level I or II athletes33 who participated in at least 50 hours of sport per year prior to their injury. Additionally, participants must have been three to nine months after unilateral ACLR and have achieved ≥ 80% quadriceps strength limb symmetry index (QI, assessed via electromechanical dynamometry, as described below), minimal to no knee effusion,34 full knee range of motion (equivalent to the uninvolved knee in flexion and
extension), the ability to hop on each leg without pain, and successful initiation of a running progression in their post-operative rehabilitation.

Exclusion criteria to control for the severity of injury were: concomitant grade III ligamentous injury, > 1 cm² full thickness chondral defects assessed via MRI or arthroscopy, or a history of previous serious injury or surgery to either lower extremity. Participants were also excluded from analysis if they sustained a second ACL injury prior to each time point tested.

**ACL-SPORTS Trial**

The methods of the larger randomized control trial, the Anterior Cruciate Ligament-Specialized Post-Operative Return to Sports (ACL-SPORTS), have been previously published. Participants received 10 physical therapy sessions of either strengthening, agility, plyometric, and secondary prevention exercises (SAP) or strengthening, agility, plyometric, and secondary prevention exercises plus perturbation training (SAP + PERT). Previous analyses of ACL-SPORTS found no difference between SAP and SAP + PERT in gait biomechanics, knee function, or patient-reported outcomes at any timepoint up to and including two years after ACLR. For the purposes of this analysis, participants were collapsed across the SAP and SAP + PERT groups.

**Present Study**

All 79 participants who were included in the parent ACL-SPORTS trial were included in the present study; readers may consult Arundale et al. for details of participant recruitment, selection, and enrollment, including a flow diagram. The present secondary analysis reports the functional performance of participants according to MOI. Participants were dichotomized by MOI, with 29 contact and 50 non-contact ACL injuries (Table 1). MOI was determined by participant self-report and verified verbally by the treating, licensed physical therapist. A contact injury was defined as contact to the knee or body directly preceding the ACL injury. Non-contact injury was defined as no contact made to the individual being injured (e.g., cutting, pivoting, landing) prior to the injury.

**Functional Testing**

Participants were evaluated post-operatively at enrollment (pre-training), after return-to-sport training (post-training), and at one and two years post-operatively on strength, hop testing, and patient-reported outcomes measures (Figure 1, Appendix B). Quadriceps strength was tested using an electromechanical dynamometer (Kin-com; DJO Global, Chula Vista, CA, USA; or System 3; Biodex, Shirley, NY, USA) during a maximal voluntary isometric contraction (MVIC). Participants were seated with their hips and knees positioned at 90 degrees and the machine’s axis of rotation aligned with the axis of rotation of the knee. The participant’s leg was strapped in at the pelvis, thigh, and shank during the MVIC testing. The uninvolved limb was tested first, followed by the involved limb, for three trials per limb. Quadriceps strength was reported as a quadriceps strength limb symmetry index. QI was calculated by dividing the involved limb maximum torque by the uninvolved limb’s maximum torque and multiplying by 100.
A series of four hop tests (single, crossover, triple hops for distance, 6-meter timed) tests were performed. Participants performed two practice trials of each hop test, then two recorded trials. The tests were always performed on the uninvolved limb prior to the involved limb and given in the same order (single, crossover, triple hops for distance, 6-meter timed). Limb symmetry indexes (LSI) of the first three single-leg hop tests were calculated by dividing the average of the two recorded trials on the involved limb by the average of the two trials on the uninvolved limb and multiplying by 100. The 6-meter timed hop was calculated by dividing the average of the two recorded trials on the uninvolved limb by the average of the two recorded trials on the involved limb and multiplying by 100 to account for a shorter time indicating a better score.

### Clinical Measures

Patient-reported outcome measures (PROMs) included the IKDC subjective knee form, the Knee Injury and Osteoarthritis Outcome Score (KOOS) sports and recreation and quality-of-life subscales, the ACL Return to Sport after Injury (ACL-RSI), the Tampa Scale of Kinesiophobia (TSK-11). The IKDC quantifies knee symptoms, function, and sports activity on a scale of 0 to 100, with a minimal clinically important difference of 11.5. The KOOS-sports and recreation subscale asks participants about the degree of difficulty with activities involving

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**Table 1. Participant Demographics**

<table>
<thead>
<tr>
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<th>Non-Contact (n=50)</th>
<th>Contact (n=29)</th>
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<td>BMI (± SD)</td>
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<tr>
<td>Sex</td>
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<td>11 Female, 18 Male</td>
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<td>Pre-Injury Level</td>
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<td>Time to Meet Enrollment Criteria (weeks)</td>
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<td>24.5 ± 8.3</td>
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<td>Second Injury by 2 Years (% population) †</td>
<td>5 (10%)</td>
<td>5 (17%)</td>
<td>0.35</td>
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**Graft Type**

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</tr>
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</table>

n= number of participants; SD= standard deviation; BMI= body mass index; BPTB= bone patellar tendon bone

* participants did not have operative reports, therefore no meniscal data were available
† Participants who sustained a second injury were excluded from all analyses that occurred after the second injury.
jumping, kneeling, and running. The KOOS-quality-of-life subscale asks participants about their daily awareness of knee problems including modifications made to their lifestyle and overall difficulty with their knee. These KOOS subscales are both calculated as a percentage from 0 to 100 with 100 indicating no impairment. Both the KOOS subscales have a minimal clinically important difference of 8. We also used the Knee Outcomes Survey-Activities of Daily Living Scale (KOS-ADLS) and the global rating of perceived knee function (GRS). The KOS-ADLS is a valid, reliable, and responsive 14 item questionnaire which assesses knee related disability by asking how well one is able to perform functional tasks, with lower scores representing greater functional limitation. The GRS is a single question asking athletes to rate their perceived knee function level from 0-100 with lower scores representing poorer function and higher indicating ability to perform all previous activities and sports without limitation. To pass the RTS criteria, we require ≥90% QI, ≥90% LSI on all four hop tests, ≥90% Knee Outcome Survey- Activities of Daily Living Scale (KOS-ADLS), and ≥90% Global Rating of Perceived Function.

To measure psychological fear of movement, we used the ACL-RSI and the TSK-11. The ACL-RSI is a valid and reliable questionnaire targeting psychological readiness to RTS. The ACL-RSI asks 12 questions about the athlete's confidence, emotions and risk appraisal, and is scored on a scale from 0 to 100. A score of 0 indicates an extremely negative psychological response. Similarly, the TSK-11 assesses pain-related fear of reinjury and ranges from 11 to 44, with higher scores indicating more fear of reinjury. The TSK-11 has been used previously in patients after ACLR and can be used to divide patients into high fear and low fear groups.

**Statistical Analyses**

All statistical analyses were performed using SPSS Version 25 (IBM Corporation, Armonk, New York, USA). A significance level of p<0.05 was set a priori. Independent t-tests and chi-squared analyses were performed to compare demographic characteristics and determine difference between groups. Participants were dichotomized into two groups, contact and non-contact, based on MOI. As all previous literature from this trial showed study participants improved across time up to and including 2 years after ACLR, data were analyzed at each time point using independent t-tests. Independent t-tests were run at every time point (enrollment, post-training, one year, two years) to determine if there was a difference between groups in QI, single-leg hop test LSIs, and scores on the KOS-ADLS, KOOS-sports and recreation and quality of life subsets, GRS, TSK-11 and ACL-RSI at 4 time points after ACLR. Secondary repeated measures ANOVAs corroborated these findings.

**RESULTS**

There were no statistically significant differences between groups in demographic or surgical characteristics, including graft type and meniscal status, or in time to meet enrollment criteria (Table 1). Both independent t-tests and secondary repeated measures ANOVA demonstrated no statistically significant or clinically meaningful differences between contact and non-contact groups in any variables at enrollment, post-training, one year, and two years after ACLR (p≥.05), with the exception of the timed hop at one year where both group’s limb symmetry indexes were > 100% (p=0.03) (Figures 2-5, Appendix A).

**DISCUSSION**

The purpose of this study was to determine if MOI influenced strength, functional performance, patient-reported outcome measures, or psychological outlook among athletes at 4 time points within the first two years following ACLR. Our findings refute our hypothesis and suggest that MOI does not influence performance on strength, functional performance, patient-reported outcome measures, or psychological outlook among athletes during the late post-operative rehabilitation phases or one or two years after ACLR in patients who are well-rehabilitated after ACLR.
point during late rehabilitation or at follow-up time points (Figure 2, Appendix A). These data suggest that athletes may progress through rehabilitation milestones similarly regardless of MOI. Functional performance was also similar at each time point, regardless of MOI (Figure 3, Appendix A). Although timed hop was statistically different between groups at one year (p = 0.03), the difference was not clinically meaningful and both groups achieved over 100% limb symmetry index (non-contact 101.1%, contact 104.6%).

Functional performance after ACLR may influence an athlete’s ability to return to preinjury sport level.54 Demonstrating poorer hop symmetry and self-reports of knee function is prospectively associated with not returning to preinjury level of sport.54 These data also indicated that patient reported outcome measures of knee function and psychological factors were not different between groups (Figure 4, Figure 5). Psychological factors, including fear of movement, fear of reinjury, confidence, and readiness to RTS may influence functional performance and outcomes after ACLR.55–58 Lentz et al. showed patients with fear of reinjury who did not RTS at one year after ACLR, compared to those who did RTS, showed significantly lower quadriceps strength at 6 and 12 months after ACLR.59 These data suggest that MOI does not impact clinical milestones in late rehabilitation and up to and including two years after ACLR.

![Figure 2](image2.png)

**Figure 2.** There were no differences in quadriceps index in contact vs. non-contact MOI at any time-point.

![Figure 3](image3.png)

**Figure 3.** There were no differences in single hop test results in contact vs. non-contact MOI at any time-point.

![Figure 4](image4.png)

**Figure 4.** There were no differences between groups on the IKDC (shown here) or any other patient reported outcome measure at any time-point. Abbreviations: IKDC = International Knee Documentation Committee Subjective Knee Evaluation Form.

![Figure 5](image5.png)

**Figure 5.** There were no differences between groups on the ACL-RSI (shown here) or TSK-II at any time-point. Abbreviations: ACL-RSI = Anterior Cruciate Ligament-Return to Sport after Injury scale.
MOI is often described by patients and referring physicians within the initial evaluation, and could influence an athlete’s rehabilitation process. Clinically, there are often biases about how MOI may affect a patient’s progression through rehabilitation. Biomechanical influences contributing to MOI, specifically non-contact MOI, are well described in the literature.7,12,30,60–62 These mechanisms are significant to our understanding of how initial ACL rupture may occur and influence prevention programs. MOI itself, however, may not inform clinicians how to treat a patient after ACLR. These data suggest late phase rehabilitation may not need to be tailored according to MOI during functional testing. These data, however, do not examine outcomes early in rehabilitation time points, and are specific to the functional outcomes we measured. There may be biomechanical differences in movement quality, and future studies should investigate biomechanical differences based on MOI. While the MOI may not be relevant to successful progression through rehabilitation, how clinicians structure both post-operative rehabilitation and RTS training is critical to safe RTS. Following criterion-based post-operative rehabilitation programs is recommended,36,63–66 which are typically divided into three phases of rehabilitation (early post-operative, middle, and late) followed by RTS training.36,63–67 The late phase of postoperative rehabilitation focuses on continued activity progression, quadriceps strength, and sport-specific interventions. Finally, the RTS phase of training consists of 10 training sessions focused on quadriceps strengthening, prevention exercises, balance, and agility and plyometric training.35 During RTS testing, participants went through a battery of functional performance tests and patient-reported outcome measures that are used to guide clinical decision making. RTS criteria in our study included ≥ 90% limb symmetry index (LSI) on 4 hop tests,68 ≥ 90% QI, and ≥90% on the KOS-ADLS and GRS.35,36 Even after athletes passed RTS criteria, immediate unrestricted RTS was withheld and athletes continued with a progression into full, unopposed sport participation.

The findings of this study suggest there is no difference in performance on functional outcomes according to contact or non-contact MOI during the late phases of post-operative rehabilitation or at one or two years after ACLR. Clinicians may ask, “Should I treat an athlete differently based on their MOI?” These data suggest that when considering functional outcomes (QI, hop testing, PROMs), late phase rehabilitation may not need to be tailored according to MOI.

Limitations
MOI can be defined in different ways, with the definition varying from study to study. Some studies report direct contact, indirect contact, and non-contact.5 Olsen et al. define a contact injury as a direct blow specifically to the knee.28 This definition, however, excludes injuries that occur with physical contact to other parts of the body. In this study, MOI was self-reported by the athlete, and confirmed verbally by a physical therapist. Contact injury was defined as contact to any part of the body immediately preceding the injury, and non-contact injury as no contact made to the athlete immediately preceding the injury. The inclusion criteria for this study are stringent, ensuring participants were ready to initiate a progressive RTS training program, and therefore we may be missing athletes who may initially perform poorly due to their MOI. The study had strict exclusion criteria controlling for concomitant injury, which excluded those with significant concomitant injury that happen with contact MOI. Data were analyzed using independent t-tests to maximize the amount of participants at each time point and detect differences in between groups. Secondary repeated measures ANOVA analyses corroborated the findings that there are no differences between groups according to MOI and that participants improve over time regardless of MOI. Although the group sample sizes represent similar frequencies of contact vs. non-contact injury similar to the literature, having more equally sized groups may have been beneficial for statistical analyses. Finally, the time points of the larger study were during the late phases of rehabilitation after clinical impairment resolution. These data do not include pre-operative or early post-operative rehabilitation time points or hip strength assessment, where differences based on MOI could exist.

CONCLUSION
The results of the current study indicate that there were no differences in strength, functional performance, patient-reported outcome measures, or psychological outlook between athletes with either
contact or non-contact mechanism of injury up to and including two years after ACLR. At each time point including pre and post-training, one year, and two years, both groups had similar performance on all functional outcome measures, indicating MOI may not influence rehabilitation outcomes. Patients following ACLR may benefit from additional strengthening, agility, and injury prevention exercises beyond traditional physical therapy regardless of MOI. MOI may not need to be considered when implementing late phase rehabilitation and RTS.

REFERENCES


APPENDIX A. MEAN DATA OF ALL FUNCTIONAL OUTCOME MEASURES. P-VALUE REPRESENTS THE UNADJUSTED P-VALUE FOR THE INDEPENDENT T-TEST COMPARISONS BETWEEN GROUPS FOR EACH VARIABLE, AT EACH TIME-POINT.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Non-Contact Mean (±SD)</th>
<th>Contact Mean (±SD)</th>
<th>P-Value</th>
</tr>
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<tr>
<td><strong>Enrollment</strong></td>
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<td></td>
<td></td>
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<tr>
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<td>74</td>
<td>89.7 (8.1)</td>
<td>93.5 (9.4)</td>
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<td>77.2 (15.1)</td>
<td>82.6 (14.4)</td>
<td>0.13</td>
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<td>Crossover Hop LSI</td>
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<td>89.5 (12.0)</td>
<td>0.10</td>
</tr>
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<td>Triple Hop LSI</td>
<td>79</td>
<td>85.1 (11.9)</td>
<td>88.7 (12.0)</td>
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<td><strong>Post-Training</strong></td>
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<tr>
<td>QI</td>
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<td>0.19</td>
</tr>
<tr>
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<td>91.9 (9.9)</td>
<td>95.8 (13.4)</td>
<td>0.19</td>
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<td></td>
</tr>
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</tbody>
</table>

n= number of participants; QI= quadriceps strength limb symmetry index; KOOS-ADLs= Knee Outcome Survey-Activities of Daily Living Subscale; GRS= Global Rating Score of Perceived Function; IKDC= International Knee Documentation Committee; KOOS= Knee Injury and Osteoarthritis Outcome Score; ACL-RSI= Anterior Cruciate Ligament-Return to Sport after Injury scale; TSK-11= Tampa Scale for Kinesiophobia

*Values are mean (Standard deviation)
† Significant t-test (p<0.05)

APPENDIX B. ATHLETES WHO DID NOT UNDERGO HOP TESTING AT EACH TIME POINT. REASON FOR NOT HOPPING (N).

<table>
<thead>
<tr>
<th></th>
<th>Non-Contact Injury (n)</th>
<th>Contact Injury (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Post-Training</strong> (15)</td>
<td>QI &lt; 80% (4), Low CAR (2), Effusion (3), Pain (2)</td>
<td>QI &lt; 80% (3), Low CAR (1)</td>
</tr>
<tr>
<td><strong>1 Year (8)</strong></td>
<td>QI &lt; 80% (1), Effusion (2), Pain (1)</td>
<td>QI &lt; 80% (2), Low CAR (1), Not reported (1)</td>
</tr>
<tr>
<td><strong>2 Years (8)</strong></td>
<td>QI &lt; 80% (1), Did not return for testing/Not reported (4)</td>
<td>Effusion (1), Not reported (1), Low back pain/stiffness (1)</td>
</tr>
</tbody>
</table>

n= number of participants; QI= quadriceps strength limb symmetry index; CAR= central activation ratio
ABSTRACT

Background: Slider exercises, which may use a gliding disc or “slider”, are dynamic exercises used for strengthening. They are proposed to increase challenge as the friction between the body and ground is decreased which increases the demands on muscles of the weight bearing limb. Hypothesis and purpose: The purposes of this study were (1) to compare the electromyographic (EMG) activity level of hip muscles of the weight bearing limb while performing a single limb slide squat to that of a standard isometric squat and (2) to investigate the influence of trunk position on hip EMG activity. It was hypothesized that the single limb slide squat would elicit greater hip EMG activity than an isometric squat and trunk position would influence EMG activity.

Study Design: Analytic, observational cross-sectional study design.

Methods: Twenty healthy male participants (age = 23.7 ± 1.3) volunteered. EMG hip muscle activation of the stance leg was measured during a single limb slide squat and as a comparison, the same leg during a standard double limb isometric squat. Both exercises where performed with a knee flexion angle of 60˚ and the trunk positioned 40˚ (flexed trunk) and 60˚ (upright trunk) relative to the floor. Surface electrodes were used to collect EMG data.

Results: EMG activity of the gluteus maximus, gluteus medius, biceps femoris and rectus femoris was significantly greater with both single limb slide exercises as compared to both squat exercises. EMG activity was greater with the flexed trunk as compared to the upright trunk for the biceps femoris.

Conclusion: Slider exercises produced a moderate or high level of activation for all muscles whereas all squat exercises produced a low-level activation.

Level of Evidence: Level 3 Mechanism-based reasoning intervention study trial.

Keywords: Electromyography, exercise, hip, lunge, Movement System
INTRODUCTION

Proximal muscular control of the hip is important for both optimal performance and injury prevention. Lack of control during activities such as landing from a jump or stepping down from a stair is associated with adduction and internal rotation of the femur, internal rotation of the tibia, and excessive pronation of the foot.1,2 This movement pattern can increase the risk of anterior cruciate ligament injuries,3 patellofemoral pain syndrome,4-7 and iliotibial band syndrome.8 Recognition of this movement pattern has led to the development of programs designed to improve hip strength and motor control.

Clinicians designing rehabilitative and preventative programs to improve hip strength and motor control typically progress from less challenging exercises to those that are more challenging. Electromyographic (EMG) activity of muscles is one method of evaluating the relative demand of different exercises. EMG of hip muscles has been reported for several hip focused exercises including squat exercises, clam exercises, lunges and lateral walks.9-12 Categorization of EMG activity as a percent of a maximal voluntary contraction (MVIC) is commonly used to assist clinicians in assessing the muscular challenge of exercises. Low-level activation exercises are described as 0-20% MVIC, moderate level 21-40%, high level 41-60% and very high >60%.13 For example, the clam exercise is considered a moderate level exercise for the gluteus medius at 40% MVIC and the gluteus maximus at 34% MVIC while a high demand exercise is represented by the single leg dead lift at 58% MVIC for the gluteus medius and 59% MVIC for the gluteus maximus.9

Slider exercises, which may use a gliding disc or “slider”, are dynamic exercises used for lower extremity strengthening. They are proposed to increase challenge as the friction between the body and ground is decreased which increases the demands on muscles of the weight bearing limb as they work to stabilize the body. While sliding discs may be used for these exercises, other options include sliding boards or simply wearing socks on a tiled floor. EMG activity of hip muscles while performing slider exercises has not been reported. The purposes of this study were (1) to compare the EMG activity of hip musculature of the weight bearing or stance limb while performing a slider exercise, referred to as the single limb slide squat, to that of a standard isometric squat and (2) to investigate the influence of trunk position on EMG activity of hip musculature while performing both exercises. It was hypothesized that the single limb slide squat would elicit greater EMG activity than an isometric squat and trunk position would influence EMG activity. Understanding EMG activity levels with this exercise in comparison to other reported hip targeted exercises will assist clinicians in designing progressively challenging exercise programs.

METHODS

In this study hip muscle activation in the weight bearing limb during a single limb slide squat was compared to that of a standard double limb isometric squat. Both exercises were performed with a knee flexion angle of 60˚ and the trunk positioned at 40˚ and 60˚ relative to the floor for a total of four exercises. Surface electrodes were used to collect EMG data during exercises, which were processed with a root mean square (RMS) algorithm, and normalized to a MVIC. A repeated measures analysis of variance (ANOVA) was conducted to detect statistical significance within the data set. A Bonferroni correction for multiple comparisons was performed to test for differences between the specific exercises. The order of the four exercises was randomized to enhance internal validity.

Participants

Twenty healthy male individuals (age = 23.7 ± 1.3, height = 182.4 ± 3.9 cm, mass = 80.5 ± 11.4 kg) volunteered to participate in this study. Participants were recruited via word of mouth. The sample size of 20 participants provided 80% power to detect effect sizes (Cohen’s d) of .50 or greater (i.e., half of a standard deviation difference) across four repeated measurements. Inclusionary criteria included being physically active at least two times per week for a minimum of 90 minutes per week and the ability to perform all four exercises with proper technique. Participants were excluded from the study if they had any lower extremity conditions limiting their ability to perform the exercises. The study was approved by the Institutional Review Board at Mayo Clinic, Rochester, MN.
**Instrumentation**

Raw EMG signals were collected with Bagnoli™ DE 3.1 double differential surface EMG sensors (Delsys Inc., Boston, MA). The sensor contacts were made from 99.9% pure silver bars 10 mm in length and spaced 10 mm apart and encased within preamplifier assemblies measuring 41 x 20 x 5 mm. The preamplifiers had a gain of 10 v/v. The combined preamplifier and main amplifier permitted a gain from 100 to 10,000. The common mode rejection ratio was 92 dB at 60 Hz, and input impedance was greater than $10^{15}$ Ω at 100 Hz. Data were collected at a sampling frequency of 1000 Hz. Raw EMG signals were processed with EMG works® Data Acquisition and Analysis software (Delsys Inc., Boston, MA).

**Procedures**

This observational cross-sectional study was completed in a research laboratory. Before participation, procedures were explained and all participants provided signed consent. Upon arrival, participants walked for five minutes as a warm-up. Each participant was asked with which leg they would kick a ball. The non-kicking, or stance leg, was used as the data acquisition leg. EMG electrodes were placed on the gluteus maximus, gluteus medius, biceps femoris, rectus femoris, and adductor longus. Electrode placement was based upon Cram's *Introduction to Surface Electromyography*, 2nd edition. All electrodes were positioned parallel to the muscle’s line of action with the gluteus maximus electrode placed halfway between the greater trochanter and the sacral spine, the gluteus medius electrode placed laterally 1/3 the distance between the iliac crest and the greater trochanter, the biceps femoris electrode placed halfway between the ischial tuberosity and the popliteal fossa and the rectus femoris electrode placed halfway between the anterior inferior iliac spine and the base of the patella. The placement of the adductor longus electrode was determined via an isometric contraction and palpation of the muscle belly. The ground electrode was placed on the anterior aspect of the proximal tibia. Prior to electrode placement, the skin was cleansed with an alcohol wipe and hair removed to reduce impedance.

To normalize the raw EMG data, the participants performed a series of maximal isometric manual muscle tests using belt fixation as assistance. The belt was used for support in order to ensure the examiner's resistance was not overmatched by the subject's force output which could compromise the results. Make tests were used for all tests. Consistent verbal encouragement was given to each subject. Participants were positioned and instructed in the muscle test procedure and then performed a 5 second practice MVIC for each muscle, which also served to set the amplifier's gain setting. After the practice MVIC, two 5 second tests were performed for all muscles of interest with the best of the two recorded.

For the gluteus maximus MVIC test, the subject was positioned prone with a pillow under the abdomen. The test leg was positioned with the hip in neutral and the knee flexed to $90^\circ$. Resistance was at the distal posterior thigh as the subject attempted to push his foot to the ceiling.

For the gluteus medius, the subject was positioned side-lying on the non-test leg. The test leg was extended and supported by the examiner in approximately $5^\circ$ of hip abduction. Resistance was proximal to the lateral malleolus as the subject attempted to lift his leg.

For the biceps femoris test, the subject was positioned prone with a pillow under the abdomen. The test leg was positioned with the knee flexed to 90 degrees. Resistance was just proximal to the ankle as the subject attempted to flex the knee.

For the rectus femoris test, the subject was positioned in short-sitting at the end of the examination table while leaning back with arms use for support. The test leg was positioned in approximately $10^\circ$ of knee flexion. Resistance was just proximal to the ankle as the subject attempted to straighten his knee.

For the adductor longus test, the subject was positioned side-lying on the test leg. The non-test leg was flexed and resting on a stool in front of his abdomen and the test leg was extended. Resistance was proximal to the ankle as the subject attempted to lift his leg.

All exercises were performed with $60^\circ$ knee flexion and the trunk either $40^\circ$ (flexed trunk) or $60^\circ$ (upright trunk) relative to the floor. The exercises are illustrated in Figure 1. The first two exercises were double-limb static squat positions. Exercise 1
was an isometric squat performed with the knees flexed to 60° in the flexed trunk position. Feet were positioned shoulder width apart. This position was held for 10 seconds. Exercise 2 was similar to exercise 1 however the trunk was in the more upright position. Exercise 3 was a single leg squat with a lateral slide while maintaining the stance knee flexed to 60° and the flexed trunk position. Exercise 4, was similar to exercise 3 however the trunk was in the upright position. For exercises 3 and 4, the initial position of the trunk and stance leg in both the frontal and sagittal plane was maintained while the slide leg was moved diagonally (lateral and back).

The path of the slide was approximately 45 degrees relative to the frontal plane of the pelvis. Tape placed on the floor served to position the subject and provide a reference for the slide path. Starting from a single limb squat position with the foot of the slide limb touching the stance limb, the subject was instructed to lightly touch the floor with the big toe of the slide limb as the foot was moved out to the side and returned to the starting position. The pace of the slide was one second to full extension and one second for the return phase. This was repeated for 10 seconds. Prior to data collection, each exercise was practiced to ensure an understanding as well as to demonstrate the ability to adequately perform the exercise. A single investigator used a hand-held goniometer to position the subject's knees. The reported Intraclass correlation coefficient for intratester reliability using a standard goniometer is .99.21 The position was monitored visually during the exercises. A Saunders digital inclinometer (The Saunders Group, Chaska, MN, USA) was used to position the trunk relative to the floor with a mid-axillary line serving as the reference. This position was attained via a hip hinge with the spine maintained with neutral curves. All exercises were performed with the subject's arms extended forward at shoulder height. Rest time was provided between each exercise. EMG data was recorded for 10 seconds for all exercises.

**Data Processing**

Raw EMG signals recorded during the five exercises were processed with the RMS algorithm at a 55-millisecond time constant, then normalized and expressed as a percentage of the MVIC. The peak EMG signal of each muscle during each exercise was determined within the 10 second interval of data collection. The peak EMG was selected as it provides a measure of the maximal activity of the muscle during an exercise.22

**Statistical Analysis**

Data were analyzed using IBM SPSS Statistics 22.0 software (IBM Corp, Armonk, NY). A repeated measures analysis of variance (ANOVA) was performed on each muscle individually, with a Bonferroni correction for multiple comparisons, to determine which exercise induced maximal recruitment in each muscle. Significance was determined with α = 0.05.

**RESULTS**

All 20 participants completed the study. Peak muscle activity during both the standard squat and slide exercise is presented in Figure 2. Repeated measures ANOVA indicated a significant difference in
EMG activation of the gluteus maximus (F = 53.118, p < 0.001), gluteus medius (F = 28.829, p < 0.001), biceps femoris (F = 45.942, p < 0.001), rectus femoris (F = 27.237, p < 0.001), and adductor longus (F = 12.289, p < 0.001) between the different exercises. Post hoc testing with Bonferroni correction for multiple comparisons found the EMG activity of the gluteus maximus, gluteus medius, biceps femoris and rectus femoris significantly greater with both slide exercises as compared to the squat exercises. EMG of the biceps femoris was significantly different between all exercise comparisons. EMG was greater in the slide exercise compared to the squat exercise and biceps femoris EMG activity in the flexed trunk position was greater than the same exercise in the upright trunk position. EMG of the adductor longus was greater with both slide exercises as compared to the squat exercises. EMG of the biceps femoris was significantly different between all exercise comparisons. EMG was greater in the slide exercise compared to the squat exercise and biceps femoris EMG activity in the flexed trunk position was greater than the same exercise in the upright trunk position. EMG of the adductor longus was greater with both slide exercises as compared to the flexed trunk position squat. The slide exercise with a flexed trunk position had greater adductor longus EMG activation than the upright trunk position squat. With the exception of the biceps femoris, trunk position did not result in a significant difference in EMG signal between “like” exercises.

DISCUSSION

The purposes of this study were to compare EMG activation of hip musculature while performing a slider exercise to that of a standard isometric squat and to investigate the influence of trunk position on EMG activity of hip musculature while performing both exercises. The first hypothesis was that slide squat exercises would require greater hip muscle activation than standard squat exercises due to the single limb support nature of the exercises combined with the perturbing influence of the striding leg on the stance limb. This hypothesis was supported for all muscles with the exception of the adductor longus. The second hypothesis that trunk position would significantly influence EMG activity for “like” exercises was supported only for the biceps femoris. All other muscles studied were not different between the flexed and upright trunk positions for “like” exercises. For all muscles, the more flexed trunk position had increased EMG activation however the difference was statistically significant for only the biceps femoris. Based on the classification of low-level activation exercises 0-20% MVIC, moderate level 21-40%, high level 41-60% and very high >60% all isometric squat exercises were low-level activation (7.2-11.3% MVIC) and all single limb squat slide exercises moderate (21.5-38.2% MVIC), with the exception of the gluteus medius slide exercise in the flexed trunk position (43.0% MVIC) which was high activation.

The trunk positions were selected to represent an athletic stance and due to evidence that a moderate trunk lean as compared to a more upright posture decreases stress on the anterior cruciate ligament (ACL) during a single-leg squat. Farrokhi et al. investigated three trunk positions during a standard lunge exercise and the influence on the EMG activation of the gluteus maximus and biceps femoris. Comparing an extended trunk or flexed trunk position to an upright trunk position, the flexed position elicited significantly greater EMG activation for both the gluteus maximus and biceps femoris compared to the neutral position. The EMG reported was 22.3% MVIC and 17.9% MVIC respectively. Comparatively, for the flexed trunk position slider exercise in the current study, the mean peak activation was 30.9±11.6% MVIC for the gluteus maximus and 33.8±23.5% MVIC for the biceps femoris. One explanation for the greater values in the current study could be Farrokhi averaged the highest one second average of normalized EMG signal whereas the peak EMG signal was reported in this study. Additionally they established MVIC in a standing position in contrast to positioning participants lying on an examination table. In the current study, there was not a significant difference in gluteus maximus activation between trunk positions. This may be due to the trunk positions being too similar. We did however
find a significant difference in biceps femoris EMG activity between trunk positions which would favor the more flexed trunk position when increased biceps femoris activation is desired such as with ACL rehabilitation exercises.

Other investigators have examined EMG activation of hip muscles to quantify the demands of various exercises.11,24-26 A recent study investigating EMG activation of hip muscles during a lunge exercise using a TRX® suspension trainer (San Francisco, CA) to suspend the trailing limb reported activation levels of 19.5% MVIC for the gluteus maximus, 24.1% MVIC gluteus medius, 13.1% MVIC biceps femoris, 13.1% MVIC rectus femoris, and 16.6% MVIC for the adductor longus.11 Mean EMG values reported were obtained over a 1 second duration surrounding the peak value during the concentric phase of the exercise. Values reported in the current study are consistently greater suggesting the slider exercise is more challenging than a suspended lunge. In addition to differences in EMG processing, an explanation may be that the lateral movement of the slide limb may introduce more perturbation and challenge to the muscles of the stance limb. Further, in the suspended lunge, stability may be provided by the trailing limb pushing into the suspension strap.

EMG activity during five unilateral weight-bearing dynamic exercises including a unilateral wall squat, mini squat, forward step-up, lateral step-up and a retro step-up has been reported.25 Muscles of interest were the gluteus maximus, gluteus medius, vastus medialis oblique, and the biceps femoris. A 1.5-second EMG signal during the concentric phase of two concentric movements was averaged and normalized to the MVIC of the respective muscle. The single limb wall squat resulted in the greatest EMG signal amplitude for the four muscles studied. They reported EMG amplitude of 86 ± 43% MVIC for the gluteus maximus and 52 ± 22% MVIC for the gluteus medius concluding the wall squat as an efficient means to strengthen hip muscles. The differences in EMG magnitude compared to values in the current study may be due to the different methods used to collect the MVIC. While manual muscle techniques with a belt fixation were used in the current study, Ayotte et al.25 used a Biodex System 2 isokinetic dynamometer (Biodex Corporation, Shirley, NY) to establish the MVIC of each muscle. Similarly, Distefano et al.9 studied the EMG amplitude of the gluteus maximus and gluteus medius in healthy participants performing 12 lower extremity strengthening exercises of varying difficulty. The mean of four repetitions for each exercise was used for analysis. Side-lying hip abduction produced the greatest activation of the gluteus medius at 81% MVIC, with the single limb squat and the single limb dead lift effective in activating both the gluteus medius (64% and 58% MVIC) and gluteus maximus (59% and 59% MVIC). In contrast to Distenfano9, muscles in a static stabilizing role and not a dynamic fashion were examined in the current study, which compromises direct comparison of EMG amplitudes.27,28 As an additional comparison, Boudreau et al.29 reported increasingly greater EMG activation for the gluteus maximus, gluteus medius, and rectus femoris starting with the single-leg step up (16.5%, 15.2%, 10.8% MVIC, respectively), to the standard lunge (21.7%, 17.7%, 19.1% MVIC), and greatest recruitment being achieved with the single-leg squat (35.2%, 30.1%, 26.7% MVIC). While they did not specify the exact parameters of EMG signal analyzed compromising direct comparison, for the same muscles in the flexed trunk position for the single limb slide squat, the current study reports 30.9%, 43.0% and 33.8% MVIC for the gluteus maximus, gluteus medius and rectus femoris, respectively. Thus, if considering a progression of exercise targeting the gluteus medius, the single limb slide squat would be a progression that may be more challenging than the single leg step-up, standard lunge or single-leg squat.

Limitations of this study include the use of surface EMG. While EMG is useful to gather information on muscle activity, it is subject to crosstalk from nearby muscles. This was minimized by utilizing standardized placement of electrodes and double-differential electrodes. In addition, EMG is not a measure of force or strength, but rather a measure of motor unit recruitment. Thus EMG information for a given exercise does not provide a definitive threshold for a strengthening stimulus. Another potential limitation was the use of a healthy active population. Results may be different in individuals with hip pathology or in different age groups.
CONCLUSIONS
These results demonstrate that based on EMG muscle activation, the lateral slide exercise with a flexed trunk elicits high activation of the gluteus medius and a moderate level exercise of the gluteus maximus, biceps femoris, rectus femoris and adductor longus. This exercise may be considered a progression from a standard or suspended lunge. The more flexed trunk position had significantly more biceps femoris EMG activity than like exercises performed in the upright trunk position. The flexed trunk position may be a preferred position if greater biceps femoris activity is desired. This information can be used by clinicians for progressing exercise programs targeting hip musculature.

REFERENCES


ABSTRACT

Background: Hip and groin problems are common in ice hockey but studies on professional female players are sparse. The available literature describes hip and groin problems by reporting incidence of time-loss injuries and may thereby underestimate the scope of these problems, which are often due to overuse and may not lead to absence from ice hockey participation.

Purpose: The purpose of this study was to describe the seasonal prevalence and severity of hip and groin problems in professional female ice hockey players. A further aim was to examine the relation between previous problems and self-reported function in the beginning of the new season.

Study design: Cross-sectional study.

Methods: Female ice hockey players from the highest league in Sweden \( n = 69 \) (19 goalkeepers, 18 defenders, 30 forwards), responded to an online survey, retrospectively assessing the prevalence of hip and groin problems (time loss and non-time loss) and their duration during the previous season. Furthermore, players reported current self-reported function on the Copenhagen Hip and Groin Outcome Score (HAGOS).

Results: Two thirds of the players experienced hip and groin problems during the previous season \( 62.3\% \) \( (N = 43) \). A quarter of the players experienced a hip and groin problem leading to time loss \( 26.1\% \) \( (N = 18) \). The majority of problems were of short (1-2 weeks) or medium (3-5 weeks) duration \( 29\% \) \( (N = 20) \) of players, respectively, while longstanding problems \( \geq 6 \) weeks were rare \( 4.4\% \) \( (N = 3) \). Players that retrospectively reported hip and groin problems during the previous season reported statistically significant impairments on all HAGOS subscales in the beginning of the new season \( p \leq 0.011 \).

Conclusion: Hip and groin problems are prevalent in professional female ice hockey players, experienced by 62\% during the previous season with resulting time-loss in 26.1\%. Reported problems were rarely of longstanding nature, but players who reported problems in the previous season had significantly impaired hip and groin function in the beginning of the new season. Even though results of this study are based on retrospective player reports this may be a first step toward a greater understanding of the true burden of hip and groin players in professional female ice hockey players.

Level of evidence: 3b

Key Words: Epidemiology; Ice Hockey; Hip pain; Groin pain; Movement system
INTRODUCTION
The number of girls and women playing ice hockey in Canada and the United States is increasing exponentially, making it one of the most rapidly growing female sports in North-America. However, continuing to play the game at the collegiate level does not come without risk. Ice hockey is among the top three sports with the highest overall game injury risk in women's collegiate sports and tops the list of sports with highest rates of groin injuries. The burden of hip and groin problems on professional players, however, is currently unknown.

Hip and groin problems have one thing in common. The main symptom is groin pain, regardless of whether the underlying cause is the hip joint or surrounding soft tissues. Muscle strains are the most common injuries to the hip and groin in ice hockey and are characterized by high recurrence rates. Considering that three quarters of all hip and groin problems in ice hockey are due to overuse, it can be argued that many of these recurrent injuries actually may be exacerbations of the same underlying problem. Players suffering from such an overuse injury do not necessarily report these problems and can often continue to train and play despite having pain. However, the current literature generally describes hip and groin injuries in ice hockey by reporting incidence rates of injuries that lead to time loss (defined as an injury resulting in inability to participate in ice hockey training or competition) or requiring medical attention (defined as an injury that is treated by a medical official, which in turn reports the injury). Hence, a large proportion of hip and groin problems in female ice hockey therefore likely never surfaces in current injury statistics. Consequently, the true burden of hip and groin problems on female ice hockey players is arguably not being captured appropriately by present reporting methods.

The choice of injury definition and reporting method in sports epidemiology should reflect the nature of the injuries aimed to be detected, and the setting in which they are to be reported. If a problem does not lead to absence from sports, using a time loss definition will not capture the full scope of these problems. The medical attention definition of injury depends on the availability of medical professionals that provide treatment and report injuries. In female ice hockey in Sweden, the access to medical care provided by clubs is limited even for professional players. For overuse injuries, such as hip and groin problems, reporting of prevalence, based on player self-report, may provide a more accurate picture of the scope of those problems than incidence rates. In soccer, this strategy has been implemented by a recent study, asking players to report existing hip and groin problems on a weekly basis. The results showed that half of all players experience hip and groin pain over the course of a season, and that traditional reporting methods would have captured just a third of these problems. Furthermore, another recent study indicates that hip and groin problems are not self-limiting and that longer duration of symptoms may have more severe and long-lasting effects on athletes' function. A similar pattern was recently observed in a study in professional male ice hockey, in which half of all participating players had experienced hip and groin problems in the previous season. Longer duration of these problems was associated with worse self-reported function in the beginning of the new season. Given the rapid increase in popularity of female ice hockey, it is surprising how little attention the sport receives in the sports medicine literature. To date, the prevalence of hip and groin problems and their relation to hip and groin function in female ice hockey has not been investigated. Furthermore, existing studies on hip and groin problems in female ice hockey solely investigate youth, collegiate or recreational athletes, while there is a complete lack of studies on the issue in professional female ice hockey players.

The purpose of this study was to describe the seasonal prevalence and severity of hip and groin problems in professional female ice hockey players. A further aim was to examine the relation between previous problems and self-reported function in the beginning of the new season.

METHOD
Study design
This cross-sectional survey study describes the magnitude and severity of hip and groin problems in professional female ice hockey players. In the beginning of the 2017/2018 season, all players of...
the highest league in Sweden [Swedish Women’s Hockey League (SWHL)] were invited to participate in an online survey. The online survey assessed prevalence and duration of experienced hip and groin problems in the previous season as well as current self-reported hip and groin function. This study was approved by the Ethics committee at Lund University (Dnr 2017/483) and reporting of results is guided by The Strengthening of Reporting of Observational Studies in Epidemiology guidelines.20

Participants and recruitment
All active players in the SWHL were eligible to participate in the study. An invitation for participation as well as the link to the online survey was provided to the SWHL clubs’ medical teams for distribution to their players. Data collection for goalkeepers was performed within the frame of a separate, prospective study using the same survey.

Questionnaire survey
The web-based survey collected data regarding player demographics such as age, height, weight, playing position and years of playing professional ice hockey. In order to determine seasonal prevalence of hip and groin problems leading to time loss, we asked players: “Did you, at any occasion during the previous season, have an injury, pain or symptoms in the hip and groin region that completely prevented you from training or match play (made you miss a match or training)?” We assessed seasonal prevalence of non-time loss problems by asking players: “Did you, at any occasion during the previous season, have an injury, pain or symptoms in the hip and groin region that affected you during training and match play (i.e. you were able to participate in matches/trainings, but meanwhile had symptoms/pain in hip/groin that affected your performance)?”. The duration of these problems was assessed by asking players for how many weeks they were unable to participate (time loss) or for how many weeks they were affected by these problems (non-time loss). Furthermore, the survey collected current self-reported hip and groin function assessed by the Copenhagen Hip and Groin Outcome Score [HAGOS; Subscales: pain, symptoms, activity of daily living (ADL), sport, physical activity (PA), and quality of life (QOL)].21

Data management and statistics
Data analysis was performed using SPSS Statistics 23 (IBM Software). Descriptive statistics were presented in form of frequencies [percentage (95%CI)] for nominal data, and median [interquartile range (IQR)] or means [standard deviations (SD)] for ordinal and ratio scale data.

HAGOS scores were computed and transformed to a 0-100 scale (0 representing extreme hip and/or groin problems and 100 representing no hip and/or groin problems) for each domain (Pain, Symptoms, ADL, Sport, PA, QOL). Duration of problems (including both non time-loss and time-loss problems) were categorized into short duration (1-2 weeks), medium duration (3-5 weeks), or long-standing (≥6 weeks). Differences in HAGOS scores in the beginning of the season between players with and without hip and groin problems (including both non-time loss and time-loss problems) during the previous season were analyzed with Mann-Whitney U test.

RESULTS
Sixty-nine players participated in the study. Inflow of players into the study is illustrated in Figure 1 and their demographics is described in Table 1.

![Figure 1. Flow of participants into the study](image)

**Table 1. Player demographics (n = 69)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age in years</td>
<td>22.0 (4.8)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169 (6.2)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>67.8 (7.2)</td>
</tr>
<tr>
<td>Years playing ice hockey (%)</td>
<td>5.8 (4.8)</td>
</tr>
<tr>
<td>Playing position (n)</td>
<td>27.5 (19)</td>
</tr>
<tr>
<td>Goalkeeper</td>
<td>26.1 (18)</td>
</tr>
<tr>
<td>Defender</td>
<td>46.4 (32)</td>
</tr>
<tr>
<td>Forwards</td>
<td>27.5 (19)</td>
</tr>
</tbody>
</table>

SD = Standard deviation; cm = centimeters; kg = kilogram
Seasonal prevalence
Two thirds of all players [n = 43; 62.3% (95%CI: 50-74)] had experienced hip and groin problems affecting their performance during the previous season [median duration: 3 weeks (IQR: 3-4)]. More than a quarter of all players [n=18; 26.1% (95%CI: 17-38)] experienced hip and groin problems leading to time loss [median duration: 1.5 weeks (IQR: 1-2.25)].

Problem duration
The majority of hip and groin problems were of short (1-2 weeks) or medium duration (3-5 weeks), and just three players reported longstanding problems (≥6 weeks) (Figure 2). Players that had experienced hip and groin problems during the previous season presented with significantly impaired self-reported function in the beginning of the new season (Table 2 & Figure 3).

DISCUSSION
The current study is the first to investigate the magnitude and burden of hip and groin problems in professional female ice hockey players. Two out of three players had experienced hip and groin problems during the previous season that negatively affected their self-reported performance. A quarter of the players had experienced hip and groin problems leading to time loss. There was a low prevalence of longstanding hip and groin problems (≥6 weeks), but players with self-reported problems during the previous season had significant impairments in self-reported function in the beginning of the new season.

Table 2. HAGOS profiles for players with and without hip and groin pain in the previous season (n=69)

<table>
<thead>
<tr>
<th>HAGOS-subscals</th>
<th>Hip and groin pain in previous season (n=43) [Median (IQR)]</th>
<th>No hip and groin pain in previous season(n=26) [Median (IQR)]</th>
<th>P-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>87.5 (77.5-95.0)</td>
<td>96.3 (88.8-100.0)</td>
<td>0.011</td>
</tr>
<tr>
<td>Symptom</td>
<td>71.43 (53.57-78.57)</td>
<td>89.28 (78.57-93.75)</td>
<td>0.000</td>
</tr>
<tr>
<td>ADL</td>
<td>90.00 (75.00-100.00)</td>
<td>100.00 (95.00-100.00)</td>
<td>0.007</td>
</tr>
<tr>
<td>Sport</td>
<td>75.00 (59.38-93.75)</td>
<td>96.88 (83.59-100.00)</td>
<td>0.001</td>
</tr>
<tr>
<td>PA</td>
<td>100.00 (100.00-75.00)</td>
<td>100.00 (100.00-100.00)</td>
<td>0.004</td>
</tr>
<tr>
<td>QoL</td>
<td>75.00 (55.00-90.00)</td>
<td>97.50 (88.75-100.00)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

HAGOS= Copenhagen Hip and Groin Outcome Score; IQR = Interquartile range; ADL = Activities of daily living; PA = Physical activity; QoL = Quality of life
* Man-Whitney U test
Two-thirds of players in this study reported having had problems during the previous season. According to these results, about 13 out of 20 players in a regular female hockey squad can expect to experience hip and groin problems over the course of a season. Most of the experienced problems did not lead to time loss from ice hockey. This is consistent with previous research suggesting that overuse injuries, characterized by gradual onset, are dominating the injury landscape for female NCAA players. Surveillance methods used in previous studies rely on the player to report an injury to medical officials or athletic trainers who are then expected to report the injury. Players may continue playing despite suffering from an overuse injury, and reporting by medical officials and athletic trainers is done on a voluntary basis. Therefore, like other overuse injuries, hip and groin problems are likely to be systematically underreported in the current literature.

By letting the players themselves report the prevalence of these problems, irrespective of whether or not they had to cease ice hockey participation, results of this study may provide a first step towards a more accurate description of their magnitude.

In this study, the severity of self-reported hip and groin problems is expressed by their duration and association with hip and groin function in the beginning of the new season. Traditionally, injury severity is expressed by the number of days lost from sport participation, which is argued against in the description of overuse problems like hip and groin problems. In this study, long-lasting hip and groin problems were rare and the majority of affected players had problem durations between one and six weeks. However, despite not being labeled as long-lasting, these problems were associated with reduced hip and groin function in the beginning of the new season. Players with problems in the previous season reported significantly worse function on all HAGOS subscales but the impairments were most marked for the three subscales symptoms, sport, and quality of life. Hip and groin pain is strongly related to self-reported sporting function in ice hockey players, and questionnaire items dealing with sport participation and quality of life have been rated the most important by patients with hip and groin problems. In their study on soccer players, Thorborg and colleagues showed similar results to the results in this study, highlighting the fact that hip and groin problems may have a long-lasting impact on the players’ hip and groin function. It has to be acknowledged that the study by Thorborg et al. included a larger sample and had far better response rates. Nevertheless, both studies indicate that, despite end of the season, long summer break, and pre-season training, players with problems during the season still present with meaningful impairments in self-reported function in the beginning of the new season, when they are expected to perform at their best.

This study is the first to describe hip and groin problems in a sample of female ice hockey players on the highest national level. In the absence of comparable data, the underlying study can be considered to be a first step towards an understanding of the scope of hip and groin problems in professional female ice hockey players. Though the absolute size of the sample is small, and the response rate for skaters low, its relative size is considered appropriate in relation to the underlying population. The sample includes 79% of all goalkeepers active in the highest Swedish hockey league, but the 25% response rate from skaters (defenders and forwards) was quite low. It is possible that skaters with a history of hip and groin problems were more likely to respond to the survey and thereby introduced a selection bias leading to an overestimation of these problems. It also has to be acknowledged that accuracy of the reported prevalence may have been affected by the fact that players had to recall hip and groin problems in the past season. Even though previous research has shown that athletes can provide valid reports of injury history one year in retrospect, prospective studies on hip and groin problems, similar to recent work on football players, are warranted in professional female ice hockey players. In the current study, seasonal prevalence of hip and groin problems was reported by the athletes themselves. It can be discussed how the validity of these reports compares to injuries reported by medical officials. However, a recent study on elite athletes reveals that a reported injury might only be the end-result of a context-dependent process in which athletes perceive to be
injured once a problem starts to hamper performance and participation. In agreement with these findings, the underlying study investigates the athlete’s perception of an injury beyond an official injury report or time-loss. Future prospective studies should make the next step and describe severity of these problems with measures of the athletes’ function such as the Oslo Sports Trauma Research Center (OSTRC) overuse injury questionnaire.28 Another important consideration is that no clinical examinations or classifications of reported problems according to consensus-based terminology were performed. However, the classification of hip and groin problems is subject to clinical uncertainty and due to the geographical spread of players across Sweden, and the lack of medical support for female players, it was not possible to perform these standardized physical examinations.

Athletes, coaches, and clinicians all have one common goal – optimizing performance and not getting injured while doing so. Results from the current study indicates that 60% of professional female ice hockey players experience hip and groin problems during a season, and those problems seem to impair the players’ ability to perform. By reducing the risk for these injuries and maintain high levels of performance, there is hence a chance to kill two birds with one stone. Problems not leading to time-loss where most common and we observed longer duration of problems to be associated with subsequent impairments in function. These results indicate that preventive efforts should not only be focused on keeping healthy players injury free (primary prevention) but also on discovering existing problems early and keep their duration as short as possible (secondary prevention). There are clinical tools to modify risk factors such as impaired adductor strength, which have shown to reduce injury risk in other sports, as well as clinical tools to screen for existing problems in ice hockey players. It is time to change the game plan and play in the offensive zone.

CONCLUSION

Two-thirds of all professional female ice hockey players had experienced hip and groin problems during the previous season, which led to time-loss for one in four of these players. Longstanding hip and groin problems were rare but self-reported hip and groin function was significantly impaired for players that had experienced problems during the previous season. Results of this study indicate that hip and groin problems are a common, not self-determining, problem in professional female ice hockey players.

REFERENCES

ABSTRACT

Background: Non-contact injuries are common in sports as abnormal lower extremity joint mechanics can place athletes at risk for injury. It is important to have reliable, feasible, cost-effective assessment tools to determine lower limb control and injury risk.

Hypothesis/Purpose: The purpose of the study was to assess the intra- and inter-rater reliability of a three-tiered anterior cruciate ligament (ACL) injury risk rating assessment of the drop vertical jump using frontal plane, two-dimensional (2-D) motion capture.

Study Design: Repeated measures.

Methods: Twenty male elite basketball athletes performed the drop vertical jump during a 2-D video assessment at Mayo Clinic Sports Medicine Center in Minneapolis, Minnesota. DVJ scores indicated the following: 1 no visible knee valgus, 2 slight wobble, inward motion of the knees, and 3 knee collision or large frontal plane knee excursion. Score assessment from video of the drop vertical jump was obtained by four independent investigators. The four raters then re-examined the same videos 1 month later, blinded to their original scores.

Results: Intra-rater reliability Fleiss Kappa measure of agreement was substantial amongst all four raters at all scoring time points: initial contact (0.672), first landing (0.728), second landing (0.670), and peak valgus (0.662) (p < 0.001). The intra-rater ICC values were good at initial contact (0.809), second landing (0.874), and max valgus (0.885), however were excellent at first landing (0.914) (p < 0.001). Inter-rater reliability Fleiss Kappa measurement scores were slight at initial contact (0.173), fair at max valgus (0.343), and moderate at first landing (0.532) and second landing (0.514; p < 0.001). Inter-rater ICC values were moderate at initial contact (0.588), excellent at first landing (0.919), and good at second landing (0.883) and max valgus (0.882; p < 0.001).

Conclusion: When comparing scores of the drop vertical jump between four independent raters across two sessions, the study demonstrated substantial Kappa and good to excellent ICC intra-rater reliability. Inter-rater reliability demonstrated slight to moderate Kappa measurements of agreement and moderate to excellent ICCs. Thus, for excellent reliability using this assessment, patients should be scored by one individual. For moderate reliability between multiple raters, the first landing of the DVJ should be scored. Findings indicate that the proposed drop vertical jump assessment may be used for reliable identification of abnormal landing mechanics.

Level of Evidence: Level 3

Keywords: Basketball, drop vertical jump, elite athlete, reliability, two-dimensional 2-D, movement screening

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INTRODUCTION
Knee injuries in sports are common, costly, and in some cases preventable. Abnormal lower extremity joint mechanics and altered neuromuscular control can place athletes at increased risk for lower extremity injuries such as an anterior cruciate ligament (ACL) tear. Three-dimensional (3-D) motion capture is considered the gold standard for movement screening. However, such testing is time consuming, expensive, requires an expert for data collection and post-processing, and is not available to most clinicians. To address these limitations, two-dimensional (2-D) video analysis has been applied to measure frontal and sagittal plane trunk, hip, knee, and ankle kinematics and associated lower extremity injury risk factors such as deficits in dynamic stability of the trunk, lower extremity asymmetries and valgus at the knee. Such testing is used for quick and easy screening with instant feedback for athletes. To determine the validity of 2-D analysis as a substitute for lower extremity 3-D analysis, reliability and validity studies have previously been conducted. Authors have found moderate correlations between 2-D and 3-D measures for the sagittal plane when running and poor correlation for the frontal plane when performing a single leg squat. Previous examiner's intra-rater reliability were excellent (ICCs: 0.951−0.963). However, many clinical studies have used 2-D analysis for assessment purposes rather than 3-D analysis. Such assessments do not require measurements but rather a "yes/no," rating assessment by an experienced reviewer. The assessment screenings are clinically useful since they are not being compared to 3-D analysis thus the measurement of a joint angle or moment is not necessary. The drop vertical jump (DVJ) is a movement tool that is sensitive for detection of increased risk of ACL injury. Researchers have found that increased knee valgus angles and external valgus moments were predictive of future ACL injury; therefore, it has been recommended that an athlete's neuromuscular control be evaluated using dynamic tasks such as the DVJ landing prior to participation in sport. The DVJ motion is easy to learn and perform, can be completed in a timely manner for a large number of subjects, and requires little space to administer. However, since previous studies focus on 3-D lower extremity risk assessments and such technology is not readily available at most clinics and current 2-D scoring assessments take more time, more analysis and more assessment, a quicker, easier to administer and analyze 2-D visual scoring assessment is needed for the DVJ motion. The purpose of the study was to assess the intra- and inter-rater reliability of a three-tiered anterior cruciate ligament (ACL) injury risk rating assessment of the drop vertical jump using frontal plane, 2-D motion capture. The hypothesis tested was that intra- and inter-rater reliability would be acceptable for use in the clinic. Results from this study will inform clinicians regarding a feasible, cost-effective, and an expedient assessment tool to access lower limb control and ACL injury risk.

METHODS

Subjects
Subjects consisted of 20 male elite basketball players. All participants gave informed consent to participate in the study which was approved by the Institutional Review Board. The athletes height (1.98 ± 0.09 m), weight (96 ± 21 kg), and age (21.7 ± 1.4 years) were recorded. All were physically active athletes, participating in elite basketball leagues.

Procedure
All athletes performed a 5-minute, self selected intensity warm up on a stationary bike. They wore athletic shoes of their choice provided by the league or their contract and were instructed to perform three DVJ's from a 31 cm high box. Instructions were as follows, “Stand with feet shoulder width apart and toes over the edge of the box. Lean forward until you fall off the box. Do not hop or step off the box but rather fall. Land equally on both feet and immediately perform a maximum vertical jump, reaching with your arms as high as possible as if jumping for a rebound in basketball.” Instructions were followed by a demonstration of the jump and emphasis on how quickly they should get off the ground and how high they should reach with both hands. Subjects underwent two to three practice repetitions and then three official jumps were video recorded using 2-D Dartfish camera (Bosch, Stuttgart, Germany) sampling at 60Hz. A camera was placed on a tripod set to the height of the athlete’s waist a, two meters
away from the box in the frontal plane. The setup was standardized across all recordings.

**DVJ Assessment and Analysis**

Four raters independently viewed and scored the DVJ videos. Three of the raters were Doctors of Physical Therapy, Board Certified in Sports Physical Therapy. The final rater was a PhD, researcher in sports medicine and biomechanics. All had five to 10 years of experience. The training procedure was a (Appendix 1) handout to each rater with a five minute explanation of the 3-tiered scoring technique. Raters were instructed to rate knee valgus, using the 3-tiered system, at four time points: 1) initial contact, 2) first landing maximum valgus, 3) second landing maximum valgus, and 4) point of maximum valgus from both jumps. The raters re-examined the same videos one month later, blinded to their original scores.

A fifth, blinded investigator compared and analyzed the results. The scores were analyzed in SPSS (v25, IBM, Armonk, NY) with the Fleiss’ Kappa23-25 and the Intraclass Coefficient Correlation (ICC$^{1,k}$) method to assess the reliability between the scores that the raters assigned for the observed knee valgus. Both analyses were used because Fleiss’ Kappa is typically used with categorical variables due to its increased accuracy of the assessment, but ICC is more recognized and interpretable by clinicians. Fleiss' Kappa's report 'level of agreement' and ICC's report consistency. Significance was set at $\alpha < 0.05$. The Fleiss' Kappa methodology calculates the degree of agreement in classification of knee valgus over that which would be expected by chance, where

$$\kappa = \frac{p - \bar{p}_s}{1 - \bar{p}_s}$$

Kappa scores are interpreted as follows: <0 = Poor agreement; 0.01 – 0.2 = Slight agreement; 0.21 – 0.4 = Fair agreement; 0.41 – 0.6 = Moderate agreement; 0.61 – 0.8 = Substantial agreement; 0.81 – 1.0 = Excellent agreement.23-25 ICC values are interpreted as follows: <0.50 = Poor reliability; 0.5 – 0.75 = Moderate reliability; 0.75 – 0.9 = Good reliability, and >0.90 = Excellent reliability.24,26

**RESULTS**

Intra-rater reliability Fleiss Kappa scores and ICC can be found in Table 1. Intra-rater Kappa levels of agreement reliability were substantial at all four time points: initial contact (0.672), first landing (0.728), second landing (0.670) and peak valgus (0.662). ICC scores (correlations) were excellent at first landing (0.914) and good at initial contact (0.809), second landing (0.874), and peak valgus (0.885). All conditional probabilities and $p$-values are reported in Table 1.

Inter-rater reliability Fleiss Kappa and ICC scores can be found in Table 2. Inter-rater agreement Fleiss Kappa was slight at initial contact (0.173), moderate for first (0.532) and second landing (0.514) and moderate for peak valgus (0.343). ICC's demonstrated moderate correlations at initial contact (0.588), excellent at first landing (0.919), and good at second landing (0.883) and peak valgus (0.882).

**DISCUSSION**

Biomechanical screening measures are commonly utilized to assess body mechanics that place athletes at risk for injury. Altered neuromuscular control contributes to abnormal lower extremity joint mechanics and can place athletes at risk for ACL injury. 2-D and 3-D motion capture have been utilized to assess the mechanics that place athletes at risk for injury.5,27,28 Previously designed tools for lower extremity screening have mixed reliability.

| Table 1. Intra-rater Fleiss Kappa levels of agreement and Intraclass Correlation Coefficient (ICC) reliability statistics for the Two-Dimensional (2D) Drop Vertical Jump (DVJ) scores. |
|-----------------|-----------------|-----------------|-----------------|
| Condition       | Fleiss’ Kappa (95%CI) | p-value | ICC(3,k) (95%CI) | p-value |
| Initial Contact | 0.672 (0.453, 0.891) | <0.001 | 0.809 (0.702, 0.877) | <0.001 |
| First Landing   | 0.728 (0.570, 0.886) | <0.001 | 0.914 (0.866, 0.945) | <0.001 |
| Second Landing  | 0.670 (0.494, 0.845) | <0.001 | 0.874 (0.803, 0.919) | <0.001 |
| Peak Valgus     | 0.662 (0.502, 0.821) | <0.001 | 0.885 (0.821, 0.926) | <0.001 |

| Table 2. Inter-rater Fleiss Kappa levels of agreement and Intraclass Correlation Coefficient (ICC) reliability statistics for the Two-Dimensional (2D) Drop Vertical Jump (DVJ) scores. |
|-----------------|-----------------|-----------------|-----------------|
| Condition       | Fleiss’ Kappa (95%CI) | p-value | ICC(3,k) (95%CI) | p-value |
| Initial Contact | 0.173 (-0.006, 0.352) | 0.058 | 0.588 (0.186, 0.819) | <0.001 |
| First Landing   | 0.532 (0.403, 0.661) | <0.001 | 0.919 (0.840, 0.964) | <0.001 |
| Second Landing  | 0.514 (0.373, 0.654) | <0.001 | 0.883 (0.768, 0.949) | <0.001 |
| Peak Valgus     | 0.343 (0.212, 0.474) | <0.001 | 0.882 (0.767, 0.948) | <0.001 |
Some authors have found poor to fair inter- and intra-rater reliability\textsuperscript{16,27,28} while others have found excellent inter- and intra-rater reliability, specifically in the tuck jump,\textsuperscript{19} drop jump tasks,\textsuperscript{5,18} and running assessments.\textsuperscript{29} Due to this discrepancy, a study was needed to determine reliability. The purpose of this study was to assess intra- and inter-rater reliability of a three-tiered drop vertical jump ACL injury risk assessment using a 2-D camera. Study results indicated substantial intra-rater agreement/reliability amongst all four raters at all scoring time points and moderate to excellent inter-rater reliability at initial contact and first landing however, kappa agreement was poor to moderate. Agreement is categorical, therefore it is much easier to have disparate results. This assessment was designed for clinicians and trainers to use with patients and athletes in the clinic or on the field. It provides a quick injury risk screen that can be used for injury risk reduction or return to play readiness following injury.

The DVJ ACL risk assessment is a new tool designed for fast athletic screening. Previous studies, though 2-D, are time consuming and require expertise in ACL related injury risk.\textsuperscript{5,18,19} The LESS Scoring system requires two cameras and 17 different scored items over the course of three different trials.\textsuperscript{18} The Tuck Jump assessment is a quicker test than the LESS as it only requires one camera but still requires scoring of 10 different criteria.\textsuperscript{19} The proposed assessment requires one camera, scores four time points, and has intra-rater reliability scores similar to previous 2-D assessments.\textsuperscript{5,18} In regards to inter-rater reliability, intra-rater scores were slightly lower however, the proposed assessment is consistent with inter-rater reliability being lower than intra-rater reliability in 2-D analysis studies.\textsuperscript{18,30}

This study is unique as it correlated results among four raters, including clinicians and researchers, rather than the more common two clinical raters. It is common in clinical testing and longitudinal research studies to have the same athlete tested by multiple people. By assessing the inter and intra rater reliability with four individuals and clinically assessing with 2D versus 3D motion, the proposed assessment is more practical and less time consuming than previous studies. The results indicate that for excellent reliability, patients should be scored by one individual. For moderate reliability between multiple raters, the first landing of the DVJ should be scored for similar grading or assessment of jump mechanics.

This study is not without limitations. Despite attempts to outline specific time points and standardize rater training, there can be subjectivity in the events of initial contact, first landing, second landing, and peak valgus. However, even with this subjectivity, there was significant reliability between raters ($p < 0.001$). The current study utilized 2-D mechanics. Frontal plane motion observed on 2-D video is not equal to the dynamic knee valgus that can be measured using 3-D techniques.\textsuperscript{4} However, Ekegren et al. found that there is an association between 2-D and 3-D analysis which makes 2D analysis of knee valgus worthy of inclusion in preliminary athlete screening.\textsuperscript{5} 2-D cameras used for the study collected at 60 hz and many cameras collect at 120hz which may provide more clarity for reviewers. The current study did not include female athletes. Future research is needed to determine repeatability in the female population.

**CONCLUSION**

The DVJ ACL risk assessment requires minimal equipment and takes less than five minutes to administer on each athlete. It is a fast, easy, and cost effective method to screen athletes in the clinic or on the field. It requires one 2-D camera (collection frequency of at least 60hz) and relies upon the visual scoring of one to four time points. The proposed three-tiered 2D DVJ frontal plane assessment is repeatable and reliable for clinical use. However, for excellent reliability, patients should be scored by one individual over time. For moderate correlations between multiple raters, the first landing of the DVJ should be scored.

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APPENDIX 1

**DROP VERTICAL JUMP 2-D ASSESSMENT**

Procedure:
- To be performed in athletic shoes
- Starting position on top of 31 cm high box
- Instructions:
  - “Stand feet shoulder width apart with toes over the edge of the box. Lean forward until you fall off the box. Do not hop off. Once you land, immediately perform a maximum vertical jump reaching with both arms as high as possible, as if jumping for a rebound in basketball.”
  - Tell the athlete you are looking to see how quickly they can get off the ground and how high they can reach with both hands.
- 2-3 practice repetitions
- 8 official trials
- Video record frontal plane

Rating:
1.) Find the frames that displays initial contact, peak valgus during first landing phase, peak valgus during second landing phase, and peak valgus over the entire motion.
2.) Rate knee valgus you see in each frame based on the key below.
3.) Average the three trials (Trial 1 + Trial 2 + Trial 3)/3
4.) Report the individual trial scores and the average.

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No knee valgus</td>
</tr>
<tr>
<td>2</td>
<td>Slight Wobble and/or Inward Motion</td>
</tr>
<tr>
<td>3</td>
<td>Knees Collide and/or Large Frontal Excursion</td>
</tr>
</tbody>
</table>

2D Video ACL Injury Risk Index

Score 1: [Image of person standing with knees slightly valgus]
Score 2: [Image of person standing with knees outwardly valgus]
Score 3: [Image of person standing with knees significantly valgus]
ABSTRACT

Background: Muscle length is a common component of the physical therapy examination, which may include the prone knee flexion (Ely) and active knee extension (AKE) tests. Clinicians using these tests should understand the clinimetric properties.

Purpose: To investigate the reliability and minimal detectable change (MDC_{95}) of the Ely and AKE tests.

Study Design: Reliability analysis.

Methods: Seventy-one asymptomatic adults (mean age 24.6 +/- 2.8 years) were recruited based on a convenience sample. Two examiners each performed the Ely and AKE test one time each in an intrasession design for the interrater reliability component, with one examiner repeating the tests one time 48 hours later to determine the intra-rater reliability. Results were recorded based on one trial per test and utilized a pelvic strap for the Ely test and an adjustable bolster for the AKE test. A separate researcher recorded measurements and results were blinded from the examiners.

Results: The Ely test had excellent intra-rater and inter-rater reliability with an intraclass correlation coefficient (ICC) (3,1) of 0.900 and ICC (2,1) of 0.914 respectively. The intra-rater and inter-rater reliability of the AKE test was good with ICC (3,1) of 0.882 and ICC (2,1) 0.886 respectively. The MDC_{95} indicated that a change greater than or equal to 8° and 12° is required to exceed the threshold of error for the Ely and AKE test respectively.

Conclusion: The Ely and AKE tests have good to excellent inter-rater and intra-rater reliability for measuring rectus femoris and hamstring muscle length when stabilization of the pelvis and hip is accounted for. The MDC should be considered as a threshold for true change in the asymptomatic adult population.

Levels of Evidence: 2b

Keywords: Active Knee Extension, Ely test, hamstring muscle tightness, lower extremity muscle length, Prone knee flexion test, rectus femoris
INTRODUCTION
Impaired muscle length or tightness is commonly observed in patients with lower extremity and lumbar injuries.1,2 Numerous variables have been implicated in the etiology of movement impairments with muscle tightness being a key factor. Muscular tightness may interfere with articular biomechanics and muscular function, potentially affecting athletic performance and predisposing an athlete to injury.3 Muscle length testing allows clinicians the ability to identify impairments that may assist in determining the most appropriate interventions and training programs. Moreover, muscle length is an outcome that is addressed among asymptomatic individuals participating in exercise and sports.4 Thus, in order to ensure accurate testing and appropriate interventions, it is essential to have reliable measurement methods and an understanding of the threshold for error within a measurement.

Tightness of the hamstrings and rectus femoris has been implicated as a risk factor for both lower extremity musculoskeletal injuries and mechanical low back pain.1,5 Researchers have linked decreased flexibility of both muscle groups with isolated muscle injury,5 patellofemoral pain syndrome,6,7 patellar tendinitis,2 and low back pain in both adults and adolescents.8 Radwan et al 1 found a direct relationship between hamstring tightness when measured via the AKE Test and self-reported severity of mechanical low back pain, especially when significant asymmetries were noted in hamstring excursion between limbs. However, a recent systematic review with meta-analysis by Hori, Hasegawa, and Tagasaki suggested that the low validity of the methods to assess flexibility may be problematic and negatively affect the strength of the research conclusions.9

Decreased hamstring excursion has also been associated with higher incidence of musculoskeletal injuries in Special Operations Forces trainees.10 Knapik et al 11 found that male military recruits with hamstring tightness were twice as likely to sustain an injury as compared to those with average flexibility; however, flexibility was not a risk factor for female recruits. Furthermore, evidence on Osgood Schlatter Disease suggests an increased incidence of the disorder in adolescent male soccer players who demonstrate rectus femoris tightness.12,13 These findings suggest that assessment of bilateral hamstring and quadriceps extensibility is a key component of a physical examination and may provide insight into an individual’s risk for a musculoskeletal lower extremity or lower back pathology.

One of the most common tests performed to assess rectus femoris tightness, the Ely Test, involves measuring the angle at the knee when the patient maximally flexes the knee actively or the therapist passively flexes the knee with the patient in a prone position.14 Peeler and Anderson implemented an objective assessment to the active Ely test by adding a goniometric measurement. This method displayed moderate reliability with an intra-rater reliability and inter-rater reliability ranging from of 0.50-0.83 (54 participants:37 males and 17 females).15 The mean score for all participants was an end range of 124° +/- 7 of knee flexion.15 One should note that the Ely test can also be performed with similar or slightly modified procedures to detect sacroiliac joint dysfunction (Yeoman test), femoral neural tension (Nachlas test) and rectus spasticity (Duncan-Ely test).16,17 The investigators of this study hypothesize that the reliability of the Ely test can be further improved by stabilizing the pelvis with a mobilization belt to further eliminate compensatory anterior pelvic tilt. This manuscript will primarily focus on the clinimetric properties of the Ely muscle length test using this methodology and a sample that more equitably represents the general population.

The reliability of the AKE test, for hamstring tightness, has been reported with intra-rater reliability between 0.78-0.94 and inter-rater reliability as high as 0.98-0.99.18-20 However, further research is warranted due to sample homogeneity, as the majority of the previous research was performed on males (55 of 61 total participants).18-20 Conner et al 20 reported the highest inter and intra-rater reliability for the AKE when using an inclinometer just distal to the tibial tuberosity to obtain an objective measurement. In their study, the untested lower extremity was supported in approximately 20° of knee flexion. The tested extremity was maintained in 90° of hip flexion supported by the participant’s upper extremity. A vertical sidebar was placed adjacent to the table to give the participant a visual reference to ensure vertical alignment of the femur.20 While this is the most reliable hamstring muscle length test to date, this study had a small sample size (15 male athletes).
Researchers have also suggested that the reliability of this test could also be improved with the addition of an external force to ensure maintenance of hip position throughout testing.\(^{20}\)

The examination of muscle length may be objectively documented utilizing instruments such as a goniometer or inclinometer during the assessment of active and passive range of motion while in specific positions thought to capture a muscle’s end-range length. Both the goniometer and inclinometer have been widely employed clinically due to their relatively low cost and portability. However, both of these instruments require the clinician to use both hands which could make joint stabilization and accurate measurement difficult. With this in mind, this study hypothesized that the utilization of a mobilization belt and an adjustable bolster would reduce measurement error and ensure reproducibility of testing for both the Ely and AKE tests. To date there is no current research analyzing this potential modification of procedures. Thus, the purpose of this study was to investigate the inter-rater and intra-rater reliability and minimal detectable change for the Ely and AKE Tests.

**METHODS**

**Participants**

A convenience sample of seventy-one asymptomatic adult (142-knees) participants, 40 women and 31 men, were recruited for this investigation from a local University setting. All participants completed a questionnaire prior to testing including their age, height, and body mass. Height and body mass were used to determine body mass index (BMI). The mean and standard deviation (SD) for the participants’ age, height, weight, and BMI were 24.6 (2.8) years, 67 (4.1) inches, 155.4 (33.3) lbs., and 24.1 (3.1) kg/m\(^2\); respectively. Inclusion criteria included males and females, ages 18-50, with absence of lower extremity pathology at the time of testing, and ability to read the English language as required to provide informed consent. Exclusion criteria consisted of participants with lower extremity pain within 48 hours of testing or participants who were unable to tolerate testing positions. Those who were selected for testing completed an informed consent document approved by the Institutional Review Board at Nova Southeastern University.

**Instruments**

An adjustable Metron® Elite Aster 3-Section Table (Performance Health; Chicago, IL) was used for all testing. A standard BASELINE® 12-inch plastic goniometer (model 12-1000, Fabrication Enterprises; White Plains, NY) was used to obtain the measurement of knee flexion for the Ely Test and hip flexion for the AKE test. A Baseline® Bubble inclinometer (model 12-1056, Fabrication Enterprises; White Plains, NY) was used to determine the final position of knee extension for the AKE test. To ensure reproducibility of testing a mobilization belt, vertical sidebar, adjustable leg rest, and 6-inch foam roller were used.

**PROCEDURES**

**Preparation**

Prior to testing, and after formal consent, each participant was required to complete a questionnaire to ensure that inclusion criteria were met. Following completion of an IRB approved consent form, participants underwent landmark marking by one researcher. With participants standing in anatomic position, Rater C used palpation to distinguish bony landmarks of the greater trochanter, tibial tuberosity, and lateral malleolus bilaterally, marking each with the body marker to ensure accuracy of goniometer and inclinometer placement throughout testing. Rater A flipped a coin to determine which lower extremity would be tested first (heads = right lower extremity, tails = left lower extremity). In the initial session, participants underwent two trials of each test with the Ely test performed first followed by the AKE test. The first trial was performed by Rater A, and the second trial by Rater B. Each subject attended a follow up session 48 hours later. At the follow up session, Rater B reassessed each muscle length test to obtain data for assessment of intra-rater reliability one time. All measurements were obtained by Rater C with blinding of the results to the other researchers. Testing at the follow up session was conducted in accordance with the initial coin toss for lower extremity sequence, as well as maintaining the order of Ely test followed by AKE to ensure consistency and minimize the effects of confounding variables on the results.

All testing and measurement were performed by three third-year doctoral physical therapy students.
under the supervision of the primary author. The raters received additional training through video and in-person instruction.

**Ely Test**

Each participant was placed in the prone position where their pelvis was strapped down to the table by the mobilization belt to eliminate compensatory anterior pelvic tilt. They were instructed to actively flex the tested knee maximally, bringing their heel toward the ipsilateral buttock, with monitoring of the ASIS throughout testing by the researcher to ensure contact with the plinth. The end position was determined by the subject's inability to further flex their tested knee without any compensation. If a compensation was observed, such as hip hiking or elevation of the pelvis from the plinth, the participant was instructed to return to the starting position and repeat the test. The examiner obtained the measurement of knee flexion in this final position using the 12″ goniometer (Figure 1). The goniometer was aligned with the participant such that the axis was placed over the fibular head, the stationary arm was aligned with the greater trochanter, and the movement arm was aligned with the lateral malleolus. A separate researcher recorded the measurement.

**Active Knee Extension Test**

The subject was instructed to lie in the supine position on the plinth with the tested leg placed over an adjustable leg rest. The contralateral leg placed on the plinth with a 6° foam roller beneath the popliteal fossa to maintain approximately 20° of knee flexion. The leg rest was adjusted to each participant to support the tested leg in 90° hip and knee flexion. The femur was then aligned with the vertical sidebar to ensure maintenance of 90° hip flexion throughout the duration of the test. A third researcher calibrated the inclinometer to zero against a vertical wall prior to each measurement to ensure consistency. The participant was then instructed to plantar flex their ankle to a comfortable position and to keep their head on the table throughout the test. The researchers monitored the participant position throughout the procedure to ensure no compensations occurred that might affect the results. A third researcher stabilized the adjustable leg rest during testing to avoid hip extension past 90° of flexion. The participant was then instructed to maximally extend the knee of the tested lower extremity while maintaining 90° hip flexion and a plantar flexed ankle. The angle of measurement was taken from the final position of knee extension with the inclinometer placed on the tibial tuberosity (Figure 2).
The participant was asked to repeat the test in the presence of the following: alteration of hip position, ankle dorsiflexion, cervical spine flexion, or inability of the participant to hold the terminal position long enough for the researcher to obtain the final measurement.

**Statistical Methods**

Data were recorded on a data collection sheet and transposed into Microsoft Excel and then imported into SPSS (SPSS Inc, Chicago, Illinois) Version 25.0 for analysis. Data was analyzed with SPSS software to determine standard deviation (SD), intraclass correlation coefficients (ICC), and mean knee angle. The inter-rater reliability of all tests was determined using the ICC Model 2,1 and the intra-rater reliability using the ICC Model 3,1. The standard error of measurement (SEM) and minimal detectable change (MDC95) were computed to determine the error threshold for both the intrarater reliability and interrater reliability with the following equations:

$$SEM = \sqrt{1 - ICC} \times SD$$  
$$MDC95 = 1.96 \times SEM \times \sqrt{2} \times SEM + \sqrt{2}$$

respectively. The standard error of measurement (SEM) was calculated to determine the precision of the mean values. The MDC95 was calculated to determine the magnitude of change needed to exceed the threshold of error at 95% confidence level. Numbers were rounded to the nearest degree to coincide with reporting values used for goniometry and inclinometer. All calculated values for inter-rater reliability and intra-rater reliability are presented in Tables 1 and 2 respectively.

**Results**

The results of this study suggest that the Ely and AKE tests have good to excellent reliability as measurement tools corresponding to the length of the rectus femoris and hamstrings respectively. The Ely test had excellent inter-rater (0.914) and intra-rater (0.900) reliability. The Ely test SEM was 3°, which equated to about 2.5% of the average measurement. This indicates that when using this measurement tool, one can be confident that the angle obtained is within 2.5% of the participants' true result. Additionally, with a minimal detectable change (MDC95) of 7-8°, one can be 95% confident that with an 8° increase or decrease in knee flexion over time, a true change in muscle length has been detected.

**Table 1. Inter-rater reliability of the Ely and Active Knee Extension (AKE) Tests**

<table>
<thead>
<tr>
<th>Test</th>
<th>Rater A Mean Angle (SD)</th>
<th>Rater B Mean Angle (SD)</th>
<th>ICC (2,1) (95% CI)</th>
<th>SEM (°)</th>
<th>MDC95(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ely</td>
<td>125.31 (8.2)</td>
<td>126.68 (9.1)</td>
<td>0.914 (0.882-0.938)</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>AKE</td>
<td>23.35 (13.5)</td>
<td>22.52 (12.4)</td>
<td>0.886 (0.844-0.917)</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

**Table 2. Intra-rater reliability of Ely and AKE Tests (Rater B)**

<table>
<thead>
<tr>
<th>Test</th>
<th>Session 1 Mean Angle (SD)</th>
<th>Session 2 Mean Angle (SD)</th>
<th>ICC (3,1) (95% CI)</th>
<th>SEM (°)</th>
<th>MDC95(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ely</td>
<td>126.68 (9.1)</td>
<td>125.85 (8.7)</td>
<td>0.906 (0.864-0.927)</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>AKE</td>
<td>22.52 (12.4)</td>
<td>22.10 (13.6)</td>
<td>0.882 (0.839-0.914)</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

**Note:** ICC – Intraclass Coefficient; CI – Confidence Interval; SD – Standard Deviation; SEM – Standard Error of Measurement; MDC95 – Minimal Detectable Change at the 95% confidence level; AKE – Active knee extension.
The AKE test demonstrated good inter-rater (0.886) and intra-rater (0.882) reliability. Mean measurements for all trials was 23° in the tested population which is comparable to previously established criteria of 20° of knee flexion remaining at the terminal position for normal adults. The standard error of measure was 4°, indicating that when using this measure one can be confident the angle obtained is within 4° of the subject’s true result. With an MDC₉₅ of 12 degrees, one can be 95% confident that with a 12° increase or decrease in knee extension over time, a true change in muscle length has been detected.

**DISCUSSION**

The findings of the current study demonstrate excellent inter-rater and intra-rater reliability for the Ely test, which suggests a high potential for achieving consistent results of rectus femoris length when tested by multiple clinicians or between multiple sessions. When assessing hamstring length, this study found the AKE test to have good inter-rater and intra-rater reliability. This suggests the ability for multiple therapists or a single therapist on multiple occasions to have a high potential for achieving consistent results when utilizing the AKE test for hamstring muscle length assessment. The authors of this study conclude both the Ely and AKE tests to be clinically appropriate and favorable due to their good to excellent reliability, efficiency of testing, and the requirement of minimal equipment, which can be found in a conventional rehabilitation setting.

As previously stated, the AKE test had good inter-rater and intra-rater reliability; however, the authors of this study considered potential explanations for decreased reliability of the assessment relative to the excellent reliability of the Ely test. The decrease in reliability of the AKE compared to the Ely test may be in part due to an increased room for error and compensation by the participant. For example, in the testing procedure for the Ely test when compared to the AKE, The Ely test utilizes the surface of the mat for stability of the femur, thereby allowing for only one plane of movement and in one direction (knee flexion) and almost no potential for compensations made by the participants throughout the testing. However, the AKE test has limited stability of the femur which allows participants to attempt to forcefully extend the testing lower extremity. In doing this, participants utilize momentum or deviate from the desired angle of hip flexion, potentially self-limited range of motion during testing. The authors believe that these variables contributed to the reliability of the AKE test when tested between raters and sessions. A bolster and foam roll were used to mitigate these changes. However, the possibility of these errors is feasible and likely concurrent to what would occur in clinical practice. Although there are studies published on the reliability of the AKE test, each utilized a different procedure and required different equipment. Therefore, future research should be conducted to determine the most reliable procedure for the AKE test while minding clinician ease in regard to time, accuracy, and equipment.

The clinical implications for these findings extend well-beyond reliability as the MDC₉₅ in particular offer clinical utility. Specifically, for the Ely test a change of 8° for the better or worse would imply change beyond the threshold of error. For the AKE a change of 12° would be needed. Thus, an improvement of hamstring flexibility would need to be 12° or greater to exceed the threshold for error. Having an understanding of error offers the clinician information useful for both change and for establishing goals.

**LIMITATIONS**

The primary limitation of this study was granting participants the freedom to engage in their regular sport and recreational activity throughout the duration of the study. Sport and recreational activity can contribute to variability in undocumented subjective reports such as soreness, stiffness, and flexibility increases or deficits secondary to timing of fitness regimens relative to either testing session. This extraneous factor would be mitigated in a follow-up study. A further limiting factor of this study is population bias. Further research is also needed to eliminate potential population bias as the participants of this study were recruited from a single data collection site (college university). A limitation of the study is generalization as the results from an asymptomatic cohort may not be appropriately disseminated to a symptomatic population. Nevertheless, muscle length testing is not limited to symptomatic
cohorts and standardization of procedures is often performed among asymptomatic individuals prior to being implemented in a clinical setting.

**CONCLUSION**

The researchers of this study found the Ely and AKE tests to have good to excellent inter-rater and intra-rater reliability suggesting that the tests are valid and reliable for measuring rectus femoris and hamstring muscle lengths in the asymptomatic adult population when appropriate stabilization and fixation of the extremities is performed. This study determined the MDC$_{95}$ for the Ely and AKE tests to be 7-8° and 12°, respectively, providing a quantitative value to determining true change as related to the threshold for error. Clinicians may use both muscle length test procedures for reliable quantitative data to determine rectus femoris and hamstring tightness and changes in muscle length over time.

**REFERENCES**


ABSTRACT

Background: The limb occlusion pressure (LOP) is determined to calculate the relative LOP. The different levels of relative LOP (percentage of LOP) influence the treatment effect and perceived discomfort during low-load blood flow restriction (BFR) strength training. Thus, determining the LOP is of the utmost importance when using BFR in clinical practice.

Purpose: The objective of this study was to investigate the concurrent validity and intra-rater (test-retest), intra-day reliability of an inexpensive, portable, easy-to-use handheld (HH) oximeter compared to a high-resolution Doppler ultrasound scanner in detecting LOP in the lower extremity.

Study design: Cross-sectional validity and reliability study

Methods: Two raters who were blinded from each other simultaneously assessed 50 healthy participants (mean age of 25.8 years). A 20 cm-wide thigh cuff with an attached sphygmomanometer was inflated until the raters independently registered the LOP with the HH oximeter and the Doppler ultrasound scanner. The test session was repeated once after a five-minute time interval.

Results: The HH oximeter recorded a non-significantly higher LOP than the Doppler ultrasound scanner, with a mean difference of 6.3 mmHg in the test session (95% limits of agreement (LoA): -16.2 to 28.8, p = 0.13) and 5.4 mmHg in the retest session (95% LoA: -13.3 to 24.0, p = 0.10). The intra-rater reliability for both devices was moderate (ICC = 0.72-0.79). The measured LOP was significantly lower (p < 0.005) in the retest session than in the test session for both the HH oximeter (mean difference: -5.7 mmHg) and the Doppler ultrasound scanner (mean difference: -4.8 mmHg).

Conclusions: The HH oximeter is a valid and reliable measuring device for determining the LOP in the lower extremity in healthy adults. The authors recommend performing at least two LOP measurements with a one-minute rest interval.

Level of Evidence: 2, Validity and reliability study

Keywords: Blood flow restriction, limb occlusion pressure, oximeter, Doppler ultrasound, validity, reliability

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INTRODUCTION
Blood flow restriction with low-load strength training (BFR-LLST) (20-40% of 1-repetition maximum [1RM]) is a novel exercise training modality intended to increase muscle hypertrophy and strength in the extremities which requires less load than traditional strength training (70-80% of 1RM). This exercise training modality seems to be highly relevant for patients who either are not allowed weight-bearing activities or experience pain during traditional strength training.1

BFR-LLST involves the application of a wrapping device, such as an inflated tourniquet/cuff or a specially designed strap,2 to restrict the arterial inflow and venous outflow to the muscle(s) during exercise. Safety is a common concern raised while performing BFR exercise, as this type of exercise can negatively affect the cardiovascular system, for example, among the elderly and immediately after surgery. Some of the specific concerns that have been raised include lower extremity muscle pain, nerve damage,3,4 and cardiovascular adverse events, such as deep venous thrombosis5,6. A factor that can impose a safety risk is high limb (arterial) occlusion pressure (LOP) during BFR-LLST, which limits or stops the arterial inflow to the muscle(s).4 The LOP is defined as the minimum occlusion pressure necessary to stop the flow of arterial blood into the lower limb distal to the cuff.7

The relative LOP is a percentage of the estimated LOP. In rehabilitation protocols for BFR-LLST, relative LOP is reported between 40% and 90%.8-10 When BFR-LLST is implemented in clinical practice, the LOP is commonly not determined.11 Despite this, very few adverse events have been reported.12

The determination of the LOP relies primarily on cuff width,13 cuff type,8 and limb circumference.14 Recently, use of a handheld (HH) Doppler (auscultatory signal) has been proposed as a valid and practical method to determine the LOP, compared to a pulse wave Doppler ultrasound.15 An alternative, inexpensive, portable, and easy method of detecting LOP could be the use of a handheld oximeter, which, in addition to monitoring an individual’s saturation, simultaneously measures the pulse rate. The sensor is placed on the index finger or the second toe, and LOP is detected when the restrictive pressure from the inflated cuff reaches a level where the pulse is undetectable on a graphical pulse frequency display (pulse stop). The validity of an oximeter also measuring the pulse rate (Zimmer Biomet, Warsaw, IN, United States), compared to that of an HH Doppler ultrasound, exhibited unacceptable accuracy in determining the LOP in the lower limb, but not in the upper limb, in a healthy population.16

To use a HH oximeter (CR-100 Handheld Pulse Oximeter, Hengzhen Coreray Technology Co., Ltd., China) for the measurement of LOP, it is crucial to assess the clinimetric characteristics, both the validity and reliability, in healthy adults. Therefore, the objective of this study was to compare an HH oximeter with a pulse wave Doppler ultrasound scanner as the reference standard in terms of its validity in detecting LOP in the lower extremity. Additionally, the intra-rater (test-retest), intra-day reliability was determined for both the HH oximeter and the Doppler ultrasound. It was hypothesized that the HH oximeter would provide a valid and reliable method for detecting LOP in healthy adults.

METHODS
Design
This study was a concurrent validity and intra-rater (test-retest), intra-day reliability study between an HH oximeter with a graphical pulse frequency display and a pulse wave Doppler ultrasound scanner. The HH oximeter was compared with the Doppler ultrasound scanner in terms of its accuracy in determining the LOP in the lower extremity. The reporting of the study was in accordance with Guidelines for Reporting Reliability and Agreement Studies (GRRAS)17 and adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines for cross-sectional studies.18

Participants
A convenience sample of 50 healthy participants was recruited from University College Absalon, Denmark. Inclusion criteria were participants aged between 18 and 70 years, able to understand and speak Danish. Participants were excluded if they had a diagnosed cardiovascular or musculoskeletal disorder, used any medication, or were pregnant. All participants were informed of the procedures and any potential risks
before they gave their written informed consent. Ethical approval was obtained from the Committee for Medical Research Ethics in the Capital Region of Denmark (identification number: 17031344).

**Instruments**

The HH oximeter (CR-100 Handheld Pulse Oximeter, Henzhen Coreray Technology Co., Ltd., China) displays the pulse (0-250 beats per minute (BPM)) rate with an interval of 1 BPM (Figure 1). The displayed hemoglobin saturation (SpO₂) was not used.

A portable high-resolution color pulse wave Doppler ultrasound scanner (SonoSite S-MSK™, FUJI-FILM SonoSite, Inc., United States) was used, with the depth set at 2.5 cm (Figure 2). Selection of an auscultatory Doppler signal was not possible on this device.

**Data Acquisition Set-up**

The measurements were taken in a quiet and temperature-controlled room (21–24°C). The test leg was randomly chosen by flipping a coin. The participants were positioned in an upright sitting position with back support, with their legs hanging freely over the edge of an examination couch. A 20 cm-wide (Heine Gamma® XXL LF, Thigh, HEINE, Optotechnik GmbH & Co., Herrsching, Germany) nylon cuff was placed around the most proximal part of the thigh. The two raters were blinded visually and auditorily from each other by a curtain and the use of earmuffs (Figure 3). The foot and instruments were cleaned with alcohol and allowed to dry before each test. One of the raters attached the adult-size finger clip SpO₂ connected to the HH oximeter to the tip of each participant’s second toe. The other rater located the dorsalis pedis artery by palpation, lateral to the extensor hallucis muscle-tendon over the navicular bone, and placed the transducer of the Doppler ultrasound perpendicular to the skin, in a water-soluble gel. The data recorder inflated the thigh cuff with a sphygmomanometer attached (Heine Gamma® G5, HEINE, Optotechnik GmbH & Co., Herrsching, Germany) to a starting pressure level of 80 mmHg and added 5 mmHg every 10 seconds until both raters signaled that they had registered the LOP, as indicated by lifting their hands. This implied that the raters measured the LOP simultaneously. The data recorder noted the level of LOP recorded by each rater. The cuff was deflated and removed; each participant then walked around in the room for two minutes. After a rest period of two minutes, the test procedure was repeated on the same leg. Between testing sessions, the participants were given a break of approximately five minutes in total. Thus, the intra-rater LOP was measured for both the HH oximeter and the Doppler ultrasound.

The participants rated their thigh pain on a numeric rating scale (NRS)\(^19\) ranging from 0 (“no pain”) to 10 (“worst possible pain”) points, and they rated their level of perceived exertion on a Borg RPE (ratings of perceived exertion) scale\(^20\) ranging from 6 (“no exertion at all”) to 20 (“maximal exertion”) points. Thigh pain at rest was rated without the cuff before and after each test session. Thigh pain and perceived exertion during the occlusion were rated immediately after the occlusion, as the recall of pain and
perceived exertion during the occlusion. This test procedure was repeated on the same leg.

Statistical Analysis
QQ-plots and histograms of the test-retest and HH oximeter-Doppler ultrasound residuals were visually examined for normal distribution. Normalized and categorical data were analyzed using parametric and non-parametric statistics, respectively. Concurrent validity between the HH oximeter and the Doppler ultrasound was assessed by a) inspecting scatter plots, with a fitted regression line of the sum of least squares; b) performing a simple linear regression to determine the Pearson correlation coefficient; and c) conducting an unpaired t-test to investigate potential differences between the means of the HH oximeter and the Doppler ultrasound. Bland-Altman plots with associated 95% limits of agreement (LoA) were used to assess the agreement between the two methods of measuring LOP. A 95% LoA (mean difference between HH oximeter and Doppler ultrasound ± 1.96 SD of the difference) was considered acceptable if the 95% LoA was ± 20 mmHg LOP. Finally, the differences between the test session and the retest session in terms of thigh pain and perceived exertion were non-normally distributed and were analyzed using the Wilcoxon matched pairs signed rank test. Linear relationships (correlation coefficient, R) between 0.40 and 0.69, 0.70 and 0.89, and 0.90 and 1.00 were interpreted as moderate, strong, and very strong, respectively. Relative intra-rater (test-retest) reliability was assessed using the intraclass correlation coefficient (ICC2,1, 2-way random effects, absolute agreement, single rater/measurement) with the corresponding 95% confidence interval (CI). Absolute intra-rater (test-retest) reliability was assessed using the standard error of measurement (SEM), calculated as $SEM = \sqrt{\text{error of mean}}$, from a two-factor repeated measures analysis of variance (ANOVA), and the smallest detectable change (SDC) (95% CI) was calculated as $SDC = SEM \times 1.96 \times \sqrt{2}$. ICC values of less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 were considered indicative of poor, moderate, good, and excellent reliability, respectively. For both the HH oximeter and the Doppler ultrasound, paired t-tests investigated the systematic differences between test sessions (test-retest), and Bland-Altman plots evaluated the heteroscedasticity of the test sessions by examining whether the magnitude of test session differences was related to the means of the two test sessions. The level of significance was set at an alpha level of p < 0.05. On the basis of previous work, a sample size of 50 participants was known to be required to achieve 80% power, 5% type 1 error, an expected ICC of 0.9, and a minimum acceptable ICC of 0.75. A total of 50 participants were therefore included. Stata 15.1 (StataCorp LLC, TX, United States) was used for all the statistical analyses.

RESULTS
Fifty-two eligible participants volunteered to participate in this study. Two participants were excluded: One participant’s data could not be used due to a technical registration error of the limb occlusion pressure, and one participant experienced dizziness during testing. Thus, 50 participants, 28 males (56%), were included in the study (Table 1). Seven of the participants (14%) had previously tried limb occlusion as part of a blood flow restriction exercise.

Validity
The scatter plots (Figure 4) and simple linear regression revealed a strong linear relationship between the two measurement methods in both the test session ($r = 0.86$, 95% CI 0.76-0.92, p < 0.001) and the
retest session ($r = 0.84$, 95% CI 0.73-0.91, $p < 0.001$), indicating strong concurrent validity.

The mean LOP measured with the HH oximeter was not significantly higher than the mean LOP measured with the Doppler ultrasound in either the test ($p = 0.13$) or the retest ($p = 0.10$) session (Table 2).

Bland-Altman plots illustrating the agreement between the HH oximeter and the Doppler ultrasound as methods for measuring LOP are presented in Figure 5. The 95% LoA is expressed as the mean difference ($\pm 1.96$ SD). The two methods of measuring LOP had a mean difference of 6.3 mmHg in the test session (LoA: -16.2 to 28.8) and a mean difference of 5.4 mmHg in the retest session (LoA: -13.3 to 24.1).

**Reliability**

The average LOP recorded by the HH oximeter was 5.7 mmHg higher in the test session (179 mmHg) than in the retest session (173.3 mmHg), indicating a systematic difference between the test sessions ($p = 0.005$) (Table 2). A similar systematic difference ($p = 0.003$) was also found for the Doppler ultrasound, which recorded an average LOP that was 4.8 mmHg higher in the test session (172.7 mmHg) than in the retest session (167.9 mmHg). The relative intra-rater (test-retest), intra-day reliability achieved by the HH oximeter and the Doppler ultrasound was moderate (ICC = 0.72) and good (ICC = 0.79), respectively. Both the HH oximeter and the Doppler ultrasound achieved acceptable absolute reliability (SEM = 10 and 8 mmHg, and SDC = 27 and 22 mmHg), respectively. (Table 3).

**Pain and Perceived Exertion**

No difference between the test and retest session was observed in terms of the level of thigh pain or perceived exertion (Table 4).
DISCUSSION

This study compared an HH oximeter with a high-resolution color pulse wave Doppler ultrasound scanner in terms of its validity in determining the LOP in the lower extremity in healthy participants. Furthermore, the intra-rater (test-retest), intra-day reliability of the HH oximeter and Doppler ultrasound in determining LOP was evaluated.

The main findings were as follows: 1) the HH oximeter provides a valid measurement in determining LOP in healthy participants; 2) the HH oximeter and the Doppler ultrasound exhibited moderate intra-rater (test-retest) reliability and measurement error in measuring LOP; and 3) a systematic difference was found between the test and retest sessions for both the HH oximeter and the Doppler ultrasound.

Explanation of results and comparison with other studies

Validity

Strong linear relationship and no significant difference were found between the HH oximeter and the Doppler ultrasound. Although the 95% LoAs (the range within which 95% of the differences between measurements by the HH oximeter and the Doppler ultrasound fell) were wide, they were considered acceptable (= ± 20 mmHg). The reason for the variation between the HH oximeter and the Doppler ultrasound seems to be multifactorial. First, the recorder incrementally increased the pressure in the cuff by 5 mmHg manually while simultaneously assessing a potential pulse stop indicated by the raters’ hands. As an alternative, a person focusing only on increasing the pressure in the cuff could have increased the agreement between the HH oximeter and the Doppler ultrasound. Second, an easy-to-use, relatively inexpensive, and portable inflatable cuff system with a standard sphygmomanometer widely used in clinical practice was pragmatically chosen. To enhance the clinical applicability to rehabilitation programs using BFR open-chain knee-extensions (i.e. quadriceps strength exercises), the participants were seated with the cuff placed around the most proximal part of the thigh. A small movement of the thigh could have changed the pressure measured by the sphygmomanometer. Third, it took approximately eight seconds for the HH oximeter to detect a change in pulse rate and, thus, a pulse stop. As the Doppler ultrasound measured a pulse stop instantly, a discrepancy in LOP recordings may have occurred.

Table 3. Intra-rater (test-retest), intra-day reliability for the handheld (HH) oximeter and the Doppler ultrasound

<table>
<thead>
<tr>
<th></th>
<th>ICC_{2,1} [95% CI]</th>
<th>SEM mmHg</th>
<th>SDC mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH oximeter</td>
<td>0.72 [0.52 to 0.83]</td>
<td>10</td>
<td>27</td>
</tr>
<tr>
<td>Doppler ultrasound</td>
<td>0.79 [0.63 to 0.88]</td>
<td>8</td>
<td>22</td>
</tr>
</tbody>
</table>

| ICC: Intraclass Correlation Coefficient |
| SEM: Standard Error of Measurement |
| mmHg: Thigh cuff pressure measured in millimeters of mercury |
| CI: Confidence Interval |
| SDC: Smallest Detectable Change with a 95% CI |

The validity of LOP in the lower extremity has been executed on similar and more costly devices, such as a pulse oximeter (Zimmer Biomet, Warsaw, IN, USA), a handheld auscultatory Doppler ultrasound, a distal-sensor-based automatic measurement...
technique,\textsuperscript{25} and a personalized tourniquet instrument with the dual purpose of controlling limb pressure and measuring pulse.\textsuperscript{26} All the studies using auscultatory Doppler ultrasound as a gold standard, except for the study using a pulse oximeter, reported no systematic differences between their device and the Doppler ultrasound.\textsuperscript{18} The distal-sensor-based technique\textsuperscript{25} and the personalized tourniquet system\textsuperscript{26} achieved similar 95% LoAs of $\pm 18$ mmHg and $\pm 26$ mmHg (outliers removed), respectively; meanwhile, a HH Doppler ultrasound achieved slightly more favorable results with a better agreement (95% LoA of $\pm 13$ mmHg) than in the present study.\textsuperscript{15} In the study by Zeng et al, LOP was assessed after the participants were allowed 15 minutes of rest in a supine position.\textsuperscript{15} The better agreement may be attributable to both a longer resting period prior to the assessment of LOP and the supine position of the participants. Finally, the pulse oximeter demonstrated a substantial disagreement, 95% LoA of $\pm 41$ mmHg (outliers removed), which was primarily explained by epidermal thickness at the sole of the first toe, temperature changes, and nail polish.\textsuperscript{16}

This indicates that the HH oximeter is comparable to other, more expensive and sophisticated devices, and more acceptable than a similar pulse oximeter, in terms of validity in detecting LOP.

Reliability
There was a significant difference between the test session and the retest session in terms of the LOP recorded by both the HH oximeter and Doppler ultrasound. The variability between multiple readings of blood pressure assessment has been described previously,\textsuperscript{27} and blood pressure readings are higher in the clinical setting than at home.\textsuperscript{28} This has been ascribed to the alerting response, anxiety, and/or a conditional response to an unusual situation, such as the first-time determination of LOP.\textsuperscript{29} At least two blood pressure recordings are recommended when the measurements are being taken in a clinical setting. If the first two readings differ by $> 10$ mmHg, a third blood pressure measurement should be taken. The blood pressure should be recorded as an average of the last two readings.\textsuperscript{28} Additionally, a study found that the LOP in the upper arm changed by up to 20 mmHg within a day and between days, and the authors of the study emphasized the necessity of taking multiple LOP measurements to account for the influence of time.\textsuperscript{10} The relative intra-rater (test-retest), intra-day reliability of the HH oximeter (ICC = 0.72) was moderate and slightly lower than that of the Doppler ultrasound (ICC = 0.79). Similar findings were observed for the absolute reliability, where the measurement error for the HH oximeter at the individual level (SDC = 27 mmHg) was slightly larger than for the Doppler ultrasound (22 mmHg).

Both the relative and absolute intra-rater (test-retest) reliability of similar devices in determining LOP\textsuperscript{23, 31} have been evaluated in studies with small sample sizes (n < 20).

For a handheld Doppler ultrasound with an automatically pressure-adjusted system and a personalized tourniquet instrument with the dual purpose of controlling limb pressure and measuring pulse, the relative reliability was found to be good (ICC = 0.8) and excellent (ICC = 0.95-0.98), respectively, and the absolute reliability (coefficient of variance (CV)) was found to be 5.5% and $\pm 2\%$ to 3%, respectively.\textsuperscript{23, 31} The CV in the present study was 3.3% (not reported in the results section). Unfortunately, the SDC was not reported in these two other studies, which represents the measurement error at an individual level in the actual units (mmHg) of the measurement. The SDC is easier to interpret in clinical practice.\textsuperscript{32}

Study Limitations and Strengths
The present study population consisted of healthy and primarily young subjects. Because validity and reliability are population-specific, the findings may not be extrapolated to populations with musculoskeletal disorders (e.g., older patients with leg injuries). This seems relevant, as it has been proposed that the measurements provided by an HH oximeter could be dependent on variables such as cold digits or poor peripheral circulation in the leg.\textsuperscript{33} The experimental set-up with a tester who simultaneously inflated the cuff and recorded the pulse stops could have caused the variation in measurements. To avoid the systematic bias between test and retest trials (reliability) for both the HH oximeter and the Doppler ultrasound, several tests or “practice” trials of the LOP should have been performed to reach stable measurements.
Future research is needed to determine the reliability and validity of the oximeter with a LOP measurement protocol consisting of at least two to three subsequent measurements with intervals of one to two minutes between tests. Finally, one participant was excluded due to a faulty reading of the LOP by the rater, and one participant withdrew due to psychological factors (dizziness). In a retrospective survey examining the side effects of BFR, dizziness was reported in a limited number of cases (two out of 12642 persons).12 On average, the participants in the present study perceived LOP determination as fairly light (Borg-exertion ≈ 12 points)20 and thigh pain as mild (NRS-pain ≈ 3 points),19,34 indicating that the determination of LOP using an HH oximeter can be considered safe.

Clinical Applicability

An HH oximeter with a portable inflatable cuff system and a sphygmomanometer is an acceptable, valid device for estimating limb occlusion pressure in the lower limb in healthy participants. In accordance with previous research, the participants’ average LOP was 5.7 mmHg higher (≈ 3%) in the first test (179.0 mmHg) than in the retest session (173.3 mmHg), indicating a systematic difference. Therefore, it is recommended to perform at least two measurements to determine LOP with a one-minute time interval between measurements. A 10 mmHg difference between readings would necessitate a third measurement. It is proposed taking an average of the last two readings.28 An advantage in clinical use would be that after the determination of the LOP, the participants/patients would not have to remove the portable inflatable cuff system, as the same system is used when engaging in BFR exercise for the lower extremity, such as knee extensions. In this study, it must be addressed that the HH oximeter was used to determine the LOP in relation to blood flow restriction exercise, not for the diagnosis of hypertension or levels of tourniquet inflation pressure in orthopedic surgery.26 A primary concern is that high LOP can completely occlude the arterial blood flow, thus imposing discomfort and a risk to the safety of the patient/participant during BFR. There is a likelihood that adverse events associated with BFR have been under-reported in the literature. Second, in order to determine the effectiveness of BFR in different populations, the dose response to different relative LOPs during BFR needs to be explored further. Therefore, the determination of LOP is vital and must occur before clinicians prescribe a BFR exercise protocol.

CONCLUSION

The HH oximeter is a valid and reliable measuring device for determining the LOP in the lower extremity in healthy adults. A systematic decrease was found from the test to the retest session; therefore, it is recommended taking at least two LOP measurements with a one-minute rest interval. An additional measurement should be taken if the first two readings differ by more than 10 mmHg. It is proposed that the average of the last two readings should be used as the LOP.

REFERENCES


ABSTRACT

**Background:** Recent research has focused on the epidemiology of shoulder and elbow injuries among high school and professional baseball players. Shoulder and elbow injury data has not been comprehensively reported among college baseball student-athletes.

**Purpose:** The purpose of this study is to describe shoulder and elbow injury rates and their characteristics among collegiate baseball student-athletes in order to improve injury prevention.

**Study Design:** Descriptive Epidemiology Study.

**Methods:** Shoulder and elbow injury data were obtained from the NCAA Injury Surveillance System for baseball from 2004-2014. Incidence rate ratios and descriptive analyses described injury characteristics for the shoulder and elbow, separately.

**Results:** The injury rate for the shoulder was 4.02/10,000 athlete-exposures and for the elbow was 2.44/10,000 athlete-exposures. During the ten-year period, the injury rate of the shoulder has approximately decreased by 75% and of the elbow by approximately 50%. Injury rates were higher during competitions compared to practice for the shoulder (rate ratio, 1.81; 95% CI, 1.51, 2.18) and elbow (rate ratio, 2.19; 95% CI, 1.73, 2.78). Freshmen and juniors were most likely to sustain shoulder (F=40.6%, J=29%) and elbow (F=33%, J=33.7%) injuries. Regarding shoulder injuries, surgery was required for 7.1%, and the outcome was season ending for 14.5%. More elbow injuries (17.5%) ended in surgery, and a greater proportion (28.9%) had season-ending injuries.

**Conclusion:** In collegiate baseball, shoulder and elbow injury rates have decreased but still result in high morbidity. More granular analyses, especially during Division 1 competitions, are necessary for more specific interventions. While shoulder injuries are more common, elbow injuries result in a longer time to return to play and a higher proportion of surgical interventions.

**Level of Evidence:** Level 3

**Keywords:** Baseball, injury surveillance, NCAA, sports injury, throwing
INTRODUCTION
Baseball is one of the most popular sports in the United States and has shown consistent growth in popularity at all levels of play. For example, at the collegiate level during the 1988-89 season there were 667 school sponsored varsity teams. In 2003-2004 that number had risen to 861, and currently, there are 950 varsity baseball teams in NCAA Divisions I-III combined.1 Even though the number of participants continues to rise, there has been a lack of epidemiological evidence investigating baseball injuries, especially at the collegiate level.

Given the increasing prevalence of shoulder and elbow injuries among high school baseball players, emphasis in the literature has been on throwing injuries in this population.2–3 The literature suggests that the incidence rate of shoulder injuries for this population is between 1.39 and 1.72 injuries per 10,000 athlete-exposures (AEs), and the majority of players returned to play within one week.2,3 Compared to shoulder injuries, elbow injuries occur at a lower rate of 0.86 injuries per 10,000 AEs, but they more frequently miss one to three weeks of participation.2 Similar to collegiate baseball, there has been limited epidemiological research focused on injuries at the Major League Baseball (MLB) level. Posner et al.6 reported that shoulder and elbow injuries accounted for 21.2% and 16.4%, respectively, of all MLB injuries recorded between 2002-2008.6 The elbow injury rate among major and minor league baseball players was 1.7 injuries per 1,000 AEs, and the average time missed from practice and competition due to an elbow injury was 27 days.4 The injury rate and time lost specific to shoulder injuries among MLB population has not been reported. Conte et al.7 highlighted that during the late 1990s shoulder and elbow injuries accounted for the greatest percentage of days that MLB players were placed on the disabled list. Additionally, the number of days on the disabled list due to elbow injuries consistently increased during this period.

A literature review revealed three epidemiological research studies investigating collegiate baseball injuries. Wasserman et al8 most recently described all injuries that occurred among the three Divisions of NCAA baseball from 2004-2014. Shoulder and clavicle injuries were the most frequently reported injury during competitions (16.0%) and practices (21.1%). Arm and elbow injuries accounted for 14.7% of all injuries during competition and 15.5% during practice.9 Dick et al.9 performed a similarly in-depth study of NCAA baseball injuries during the 1988-2004 seasons. Their results were similar in that shoulder injuries were among the most common injuries during competitions (16%) and practices (23.4%) and elbow injuries made up fewer competition injuries (9.3%) and practice injuries (10.8%).9 A two-year report of baseball injuries at a Division I college had similar findings that the majority of all injuries are to the shoulder (24%), and 12% of all injuries occur to the elbow.10 While these studies highlight shoulder and elbow injury occurrences, their purposes were to provide a comprehensive analysis of all baseball injuries. So, they do not provide information about the circumstances specific to shoulder and elbow injuries. Furthermore, given the emphasis on shoulder and elbow injury prevention during the past two decades, a reevaluation of injury occurrence and the characteristics of shoulder and elbow injuries are recommended.

Shoulder and elbow injuries have a dramatic impact on the overall injury rate and time lost from participation at all levels of baseball. While recent epidemiological studies at the high school and professional levels have specifically targeted shoulder and elbow injuries to better define and understand the injury causation, no research that specifically analyzes shoulder and elbow injuries among collegiate baseball student-athletes could be found. Therefore, the purpose of this study is to describe shoulder and elbow injury rates and their characteristics among collegiate baseball student-athletes in order to improve injury prevention.

METHODS
To analyze injury event data of collegiate baseball student-athletes who had sustained a shoulder or elbow injury, data from the National Collegiate Athletic Association (NCAA) Injury Surveillance System (ISS) was used for the 2004-2014 academic years. The ISS is managed by the Datalys Center for Sports Injury Research and Prevention. Data analysis was specific to injury data from the championship segment that occurs from February to June in Division I and
January to May in Division II and III when colleges compete in conference and NCAA championship tournaments. The ISS does not collect injury data during the non-championship segment that occurs in the Fall. A national volunteer sample of Division I, II, and III NCAA institutions provide exposure and injury data via an internet-based application. Participating institutions vary each year and for each sport. Sampling and data collection methods as well as other system details have been previously described.11

Members of the medical staff at each institution input the data for each injury and the daily athlete-exposure (AE) summaries. Each injury is defined by the injured body part and specific type of injury. For data acquired during 2004-2008 academic years, the ISS defined a reportable injury as having occurred during organized collegiate practice or competition that required the attention from an athletic trainer or physician and resulted in the restriction of participation for at least one day beyond the day of injury. Starting in 2009-2010, the ISS also began monitoring non-time-loss injuries which required the student-athlete to be evaluated or treated (or both) by an athletic trainer or physician but did not restrict participation for more than the day of injury. For the purpose of this paper, and to be consistent across all of the academic seasons that were analyzed, the analysis included only injuries that resulted in time lost from participation beyond the day of injury and that were designated as occurring to the shoulder or elbow. The ISS defined a reportable AE as one student-athlete participating, regardless of the amount of time, in a NCAA-sanctioned activity in which he or she was exposed to the possibility of athletic injury. An AE during competition required that the student-athlete have actually acquired playing time.11

The ISS standardizes the characteristics that the medical staff use to describe an injury event in baseball. For this manuscript the following characteristics were analyzed for the 2004-2014 seasons: Division, event type, time of season, injury diagnosis, recurrence type, player position, basic mechanism, specific mechanism, surgery, and outcome. The student-athletes’ grade levels (academic year) were collected by the ISS for only the 2009-2014 seasons. The injury rates of the shoulder and elbow were calculated for total exposures, Division exposures, competition and practice exposures, and time of season exposures using unweighted counts per 10,000 AEs and adjusting for Division and year. Incidence rate ratios (IRR) and 95% confidence intervals were calculated to compare rates between categories of an exposure variable while also adjusting for Division and year. If the value of one was included in the 95% CI, then the IRR was interpreted as equal rates occurring between the variable’s categories. If the 95% CI did not include the value of one then results were considered statistically significant. IRR less than one indicates a decreased injury risk for a variable’s category relative to the referent category. IRR greater than one indicates an increased risk of injury in a variable’s category relative to the referent category.

RESULTS

Shoulder Injury Incidence Rates

During the 2004-2014 academic years, 463 shoulder injuries and 804,740 AEs were recorded in the ISS. The injury rate for all shoulder injuries was 4.02 (95% CI = 3.50, 4.60) per 10,000 AEs, and the point estimates demonstrate a steady decline of 79% from 8.0 to 1.7 injuries per 10,000 AEs during the period of 2004 to 2014 (Figure 1). Student-athletes playing at the Division I level were significantly more likely to sustain a shoulder injury than those playing in Division II (IRR = 1.49; 95% CI 1.16, 1.92) or Division III (IRR

![Figure 1. Shoulder and elbow injury rates per 10,000 athlete-exposures and 95% confidence intervals by academic year for all baseball student-athletes.](image-url)
There was no difference in the incidence rate of shoulder injuries between Division II and Division III (Table 1). Shoulder injuries were 81% more likely to occur during competition (IRR = 1.81; 95% CI 1.51, 2.18) (Table 2). Compared to the postseason, significantly higher incidence rates occurred during the preseason (IRR = 2.34; 95% CI 1.35, 4.06), and in-season (IRR = 1.94; 95% CI 1.21, 3.34). However, there were no differences in the incidence rates between preseason and the in-season (IRR = 1.19; 95% CI 0.98, 1.44) (Table 3).

Shoulder injury characteristics
Among all Divisions between 2004-2014 academic years, a national estimate of 11,575 shoulder injuries (95% CI, 10,554, 12,597) occurred. The five most commonly reported injuries are listed in Table 4. The most common positions sustaining shoulder injuries were pitchers (45.9%) and fielders (24.6%). The majority of injuries (78.5%) were classified as new injuries. Of the recurrent injuries, 13.9% were recurrences from a previous season. 72.8% of the shoulder injuries were non-contact, and of these 33.4% were classified as an overuse injury or having a gradual onset. 52% of shoulder injuries resulted in a loss of playing time for two weeks or less while 14.5% of injuries were non-contact, and of these 33.4% were classified as an overuse injury or having a gradual onset.
ended the student-athlete's season. Freshmen made up the largest cohort (40.6%) of student-athletes with shoulder injuries (Figure 2). A summary of shoulder injury characteristics is provided in Table 5.

### Elbow injury incidence rates

During the previously mentioned time-period, 281 elbow injuries in association with the same 804,740 AEs were reported to the ISS. The injury rate of all elbow injuries was 2.44 (95% CI = 2.09, 2.85) per 10,000 AEs, and during the period 2004 to 2014, the injury rate decreased by 48% from 4.0 to 2.1 injuries per 10,000 AEs (Figure 1). Division I student-athletes had a significantly higher rate of elbow injuries than those who play Division II. There were no other significant differences between Divisions (Table 6). Elbow injuries were more than twice as likely to occur during competitions compared to practice (IRR = 2.19; 95%CI 1.73, 2.78), (Table 7) and there were no differences in the injury rates between the times of season (Table 8).

### Table 5. Cases, national estimates (NE) and percentage of national estimates (%NE), 95% confidence interval, for shoulder injury characteristics

<table>
<thead>
<tr>
<th>Injury Recurrence</th>
<th>Cases</th>
<th>NE</th>
<th>%NE (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>355</td>
<td>9015</td>
<td>78.5 (73.6, 83.5)</td>
</tr>
<tr>
<td>Recurrent from Previous Season</td>
<td>66</td>
<td>1605</td>
<td>13.9 (9.9, 17.9)</td>
</tr>
<tr>
<td>Recurrent from Same Season</td>
<td>36</td>
<td>854</td>
<td>7.6 (4.3, 10.9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Baseball Position</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitcher</td>
<td>194</td>
<td>5281</td>
<td>45.9 (39.6, 52.3)</td>
</tr>
<tr>
<td>Infield</td>
<td>56</td>
<td>1763</td>
<td>15.2 (10.1, 20.4)</td>
</tr>
<tr>
<td>Outfield</td>
<td>41</td>
<td>1078</td>
<td>9.4 (5.4, 13.4)</td>
</tr>
<tr>
<td>Catcher</td>
<td>7</td>
<td>247</td>
<td>2.1 (0.1, 4.2)</td>
</tr>
<tr>
<td>Baserunner</td>
<td>31</td>
<td>616</td>
<td>4.0 (2.1, 5.8)</td>
</tr>
<tr>
<td>Batter</td>
<td>23</td>
<td>376</td>
<td>1.8 (0.7, 2.8)</td>
</tr>
<tr>
<td>Other</td>
<td>105</td>
<td>2112</td>
<td>21.5 (17.1, 26.0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic Injury Mechanism</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute – Contact</td>
<td>97</td>
<td>2704</td>
<td>23.8 (18.0, 29.7)</td>
</tr>
<tr>
<td>Acute – Noncontact</td>
<td>177</td>
<td>4533</td>
<td>39.4 (33.3, 45.5)</td>
</tr>
<tr>
<td>Gradual / Overuse</td>
<td>177</td>
<td>3872</td>
<td>33.4 (27.9, 39.4)</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>365</td>
<td>3.2 (0.1, 6.2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specific Injury Mechanism</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitching</td>
<td>180</td>
<td>4415</td>
<td>39.3 (33.2, 45.5)</td>
</tr>
<tr>
<td>Throwing</td>
<td>121</td>
<td>3019</td>
<td>26.9 (21.1, 32.7)</td>
</tr>
<tr>
<td>Non-throwing</td>
<td>153</td>
<td>3782</td>
<td>33.7 (27.6, 39.9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surgery</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>42</td>
<td>806</td>
<td>7.1 (4.1, 10.1)</td>
</tr>
<tr>
<td>No</td>
<td>411</td>
<td>10192</td>
<td>88.6 (83.8, 93.5)</td>
</tr>
<tr>
<td>Unknown / Missing</td>
<td>4</td>
<td>475</td>
<td>4.3 (0.0, 8.7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outcome (Time Loss)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6 days</td>
<td>148</td>
<td>3868</td>
<td>33.7 (27.7, 39.7)</td>
</tr>
<tr>
<td>7-13 days</td>
<td>75</td>
<td>2108</td>
<td>18.3 (12.9, 23.8)</td>
</tr>
<tr>
<td>14-29 days</td>
<td>79</td>
<td>1973</td>
<td>17.2 (12.4, 22.0)</td>
</tr>
<tr>
<td>30 + days</td>
<td>63</td>
<td>1434</td>
<td>12.5 (8.7, 16.3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Season Ending</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Season Ending</td>
<td>170</td>
<td>4912</td>
<td>14.5 (9.9, 19.2)</td>
</tr>
<tr>
<td>Career Ending*</td>
<td>1</td>
<td>12</td>
<td>0.1 (0.0, 0.3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Athlete chooses to depart team*</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Athlete released from team*</td>
<td>16</td>
<td>301</td>
<td>2.6 (1.3, 3.9)</td>
</tr>
<tr>
<td>Athlete released from team*</td>
<td>5</td>
<td>107</td>
<td>0.9 (0.1, 1.8)</td>
</tr>
</tbody>
</table>

*Only reported for 2004-2009 seasons

### Table 6. Elbow injury rates per 10,000 athlete-exposures (AEs) of elbow injuries among collegiate baseball student-athletes by division

<table>
<thead>
<tr>
<th>Division</th>
<th>Injuries (n)</th>
<th>AEs (n)</th>
<th>Injury Rate* (per 10,000 AEs)</th>
<th>aIRR* (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Division I</td>
<td>141</td>
<td>356202</td>
<td>2.4</td>
<td>Referent</td>
</tr>
<tr>
<td>Division II</td>
<td>48</td>
<td>177757</td>
<td>2.1</td>
<td>0.68 (0.49, 0.79)</td>
</tr>
<tr>
<td>Division III</td>
<td>92</td>
<td>269745</td>
<td>2.6</td>
<td>0.86 (0.66, 1.12)</td>
</tr>
</tbody>
</table>

aIRR expressed as inverse ratio for interpretation of Division I relative to Division II and Division III, as appropriate

### Table 7. Elbow injury rates per 10,000 athlete-exposures (AEs) among collegiate baseball student-athletes by event type

<table>
<thead>
<tr>
<th>Event</th>
<th>Injuries (n)</th>
<th>AEs (n)</th>
<th>Injury Rate* (per 10,000 AEs)</th>
<th>aIRR* (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practice</td>
<td>132</td>
<td>524720</td>
<td>1.6</td>
<td>Referent</td>
</tr>
<tr>
<td>Competitions</td>
<td>149</td>
<td>380021</td>
<td>3.6</td>
<td>2.19 (1.73, 2.78)</td>
</tr>
</tbody>
</table>

aIRR = adjusted injury rate ratio
This study used the National Collegiate Athletic Association (NCAA) Injury Surveillance Program (ISS) to analyze shoulder and elbow injuries among baseball student-athletes for a 10-year period from the 2004-2005 academic year through the 2013-2014 academic year. During this time, the overall injury rate for the shoulder was 4.02 (95% CI = 3.50, 4.60) per 10,000 AE.s. Wasserman et al.8 used the same data set as the current study, so the rates for comparison between shoulder or elbow injuries were not estimated. Dick et al.9 reported the injury rate for all body parts during competition and practice, separately, for NCAA baseball seasons between 1988-2004. Using the data provided, an overall shoulder injury rate of approximately 5.6 /10,000 AE.s was estimated for that era.

In comparison, the shoulder injury rate among high school baseball players is significantly lower at 1.4 - 2.3 injuries / 10,000 AE.s.3,5 The literature describing major and minor league baseball shoulder injuries is less descriptive.6,12,13 However, the incidence of shoulder injuries is very comparable as 15% of all reported NCAA baseball injuries were shoulder injuries as compared to 19-21% among professional baseball.6,12,13

The injury rate found in this investigation for the elbow was 2.44 (95% CI = 2.09, 2.85) / 10,000 AE.s. A very similar rate of approximately 2.9 elbow injuries per 10,000 AE.s was estimated for NCAA baseball student-athletes between 1988-2004.9 Similar to the

### Table 8. Elbow injury rates per 10,000 athlete-exposures (AE.s) among collegiate baseball student-athletes by season

<table>
<thead>
<tr>
<th></th>
<th>Injuries (n)</th>
<th>AE.s (n)</th>
<th>Injury Rate* (per 10,000 AE.s)</th>
<th>alIRR† (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preseason</td>
<td>88</td>
<td>257185</td>
<td>2.6</td>
<td>Referent</td>
</tr>
<tr>
<td>Inseason</td>
<td>182</td>
<td>514582</td>
<td>2.3</td>
<td>1.00 (0.77, 1.30)</td>
</tr>
<tr>
<td>Postseason</td>
<td>11</td>
<td>32974</td>
<td>3.1</td>
<td>1.19 (0.74, 1.70)</td>
</tr>
</tbody>
</table>

* Adjusted by year and division
†alIRR expressed as inverse ratio for interpretation of the preseason relative to the inseason and postseason, as appropriate.
‡Referent category for specific alIRR
alIRR = adjusted injury rate ratio

### Elbow injury event characteristics

Throughout the study period among all Divisions, a national estimate of 7,375 elbow injuries (95% CI, 6,575, 8,175) were reported. The four most common injuries are listed in Table 9. Pitchers were identified for 62.1% of all elbow injuries, fielders made up 12.4% and offensive players claimed 12.9% of all elbow injuries. The majority of injuries (76.4%) were reported as new injuries, and 12.9% were recurrences from a previous season. The vast majority (82%) of the elbow injuries were non-contact. 47.4% were classified as an acute non-contact injury, and specifically, the majority of elbow injuries (56.3%) occurred while the student-athlete was pitching. 39.9% of elbow injuries resulted in a loss of playing time for two weeks or less while 28.9% ended the student-athlete’s season. 17.5% of elbow injuries resulted in surgery. Freshmen (33%) and juniors (33.7%) made up approximately equal proportions of student-athletes with elbow injuries (Figure 3). A summary of elbow injury characteristics is provided in Table 10.

### Table 9. Cases, national estimate (NE), and percentage of national estimate (%NE) of all elbow injuries, 95% confidence interval, of most common elbow injuries

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Cases</th>
<th>NE</th>
<th>%NE  (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulnar Collateral L menagament Sprain</td>
<td>127</td>
<td>3085</td>
<td>42.1 (34.2, 50.0)</td>
</tr>
<tr>
<td>Medial Epicondylitis</td>
<td>43</td>
<td>892</td>
<td>12.2 (8.2, 16.1)</td>
</tr>
<tr>
<td>Contusion</td>
<td>34</td>
<td>828</td>
<td>11.3 (7.0, 15.6)</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>9</td>
<td>676</td>
<td>9.2 (3.2, 15.2)</td>
</tr>
</tbody>
</table>

### Figure 3. Elbow injury frequency by the student-athlete’s academic year in school. Data available only for 2009-2014.

### Discussion

This study used the National Collegiate Athletic Association (NCAA) Injury Surveillance Program (ISS) to analyze shoulder and elbow injuries among baseball student-athletes for a 10-year period from the 2004-2005 academic year through the 2013-2014 academic year. During this time, the overall injury rate for the shoulder was 4.02 (95% CI = 3.50, 4.60) per 10,000 AE.s. Wasserman et al.8 used the same data set as the current study, so the rates for comparison between shoulder or elbow injuries were not estimated. Dick et al.9 reported the injury rate for all body parts during competition and practice, separately, for NCAA baseball seasons between 1988-2004. Using the data provided, an overall shoulder injury rate of approximately 5.6 /10,000 AE.s was estimated for that era. In comparison, the shoulder injury rate among high school baseball players is significantly lower at 1.4 - 2.3 injuries / 10,000 AE.s.3,5 The literature describing major and minor league baseball shoulder injuries is less descriptive.6,12,13 However, the incidence of shoulder injuries is very comparable as 15% of all reported NCAA baseball injuries were shoulder injuries as compared to 19-21% among professional baseball.6,12,13

The injury rate found in this investigation for the elbow was 2.44 (95% CI = 2.09, 2.85) / 10,000 AE.s. A very similar rate of approximately 2.9 elbow injuries per 10,000 AE.s was estimated for NCAA baseball student-athletes between 1988-2004.9 Similar to the
shoulder, when using a large national database, high school elbow injury rates were much lower at 0.86 /10,000 AEs. The incidence of elbow injuries among professional baseball players has been reported to be 7.8-16.4% of all Major League injuries and 9.8-11.3% of all Minor League injuries. Our results are comparable as 9.1% of all injuries were to the elbow.

The injury rates of shoulder and elbow demonstrated similar trends as they marginally increased from 2004-2006 before peaking in 2006-2007 and then steadily decreased until a large reduction in 2009-2010. From 2009 through 2014 the injury rates have remained consistent (Figure 1). While differences in school participation rate and the data collection procedures may have created a reporting bias, thereby influencing the observed rate changes, the cause of the decline is uncertain. Starting in the early 2000s, attention was brought in the literature to the increasing rate of shoulder and elbow injuries among youth baseball players. As a result, the American Sports Medicine Institute released a position statement, which has since been updated, to address the increased rate of shoulder and elbow injuries among youth baseball players. Among high school baseball players, the shoulder injury rate decreased by approximately 50% from 2005 to 2007 and has since remained relatively stable. Elbow injury rates have slightly increased but have become consistent at approximately one elbow injury / 10,000 AEs. The attention given to the prevalence of upper extremity injuries in youth baseball may have increased the emphasis on injury prevention for the young players which translated into decreased injury rates of collegiate baseball players in subsequent years.

Division I baseball student-athletes showed a statistically significant increase of injury rate compared to Division II and III student-athletes for shoulder injuries (Table 1). Elbow injury rates are not as consistent as Division I student-athletes had significantly more injuries than only Division II student-athletes (Table 6). There were no differences between Division II and III for either shoulder or elbow injury rates. Similar differences of injury rates between NCAA Divisions in various sports and between the levels of professional sports have been reported. The cause of this difference between Divisions is multifactorial but most likely impacted

<table>
<thead>
<tr>
<th>Table 10. Cases, National Estimate (NE), Percentage of national estimate (%NE), 95% Confidence Interval, for elbow characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury Recurrence</td>
</tr>
<tr>
<td>Cases</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>New</td>
</tr>
<tr>
<td>Recurrent from Previous Season</td>
</tr>
<tr>
<td>Recurrent from Same Season</td>
</tr>
<tr>
<td>Baseball Position</td>
</tr>
<tr>
<td>Cases</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Pitcher</td>
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<tr>
<td>Infield</td>
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<tr>
<td>Outfield</td>
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<tr>
<td>Catcher</td>
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<tr>
<td>Baserunner</td>
</tr>
<tr>
<td>Batter</td>
</tr>
<tr>
<td>Other</td>
</tr>
<tr>
<td>Basic Injury Mechanism</td>
</tr>
<tr>
<td>Cases</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Acute – Contact</td>
</tr>
<tr>
<td>Acute – Noncontact</td>
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<tr>
<td>Gradual / Overuse</td>
</tr>
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<td>Other</td>
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<tr>
<td>Specific Injury Mechanism</td>
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<td>Cases</td>
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<td>-------</td>
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<tr>
<td>Pitching</td>
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<tr>
<td>Throwing</td>
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<tr>
<td>Non-throwing</td>
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<td>Surgery</td>
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<td>Cases</td>
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<td>-------</td>
</tr>
<tr>
<td>Yes</td>
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<tr>
<td>No</td>
</tr>
<tr>
<td>Unknown / Missing</td>
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<tr>
<td>Outcome (Time Loss)</td>
</tr>
<tr>
<td>Cases</td>
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<tr>
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<tr>
<td>1-6 days</td>
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<tr>
<td>7-13 days</td>
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<td>14-29 days</td>
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<tr>
<td>30 + days</td>
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<tr>
<td>Season Ending</td>
</tr>
<tr>
<td>Career Ending*</td>
</tr>
<tr>
<td>Athlete chooses to depart team*</td>
</tr>
<tr>
<td>Athlete released from team*</td>
</tr>
</tbody>
</table>

*Only reported for 2004-2009 seasons
by the increased skill level and intensity of play in Division I athletics. Although many major league players transition directly from high school or from other countries into the minor league system, professional players who attended college are predominantly from Division I schools. As such, players who are more highly skilled and opt to go to college are more likely to play at Division I schools. These student-athletes, therefore, may have been exposed to more year-round baseball specific training and enter college with predisposing factors for shoulder and elbow injuries. Meanwhile, Division II and III baseball athletes may have been more diverse in their sports participation during high school which maintained the integrity of shoulder and elbow structures and decreased the opportunity for injury.

Distinctions in the regulations that govern practice and competition scheduling between Divisions do not appear responsible for injury rate differences. Divisions I and II have similar structures; however, Division I schools have significantly higher injury rates than Division II schools for shoulder and elbow injuries. For Division III schools, NCAA bylaws permit fewer exposure opportunities as they have fewer competitions, shorter durations of the non-championship segment season and preseason, and no organized off-season practices. However, Division III schools reported significantly lower injury rates only from Division I schools for shoulder injuries. There does not appear to be any consistent pattern to indicate that NCAA regulations influence the differences in shoulder and elbow injury rates between Divisions.

In the current study, injury rates were higher in competition versus practice for both shoulder and elbow injuries (Tables 2 and 6). These findings have been commonly described within other collegiate sports and high school baseball.\(^2,^5,^8,^8,^9\) It is hypothesized that the overall increase in injury rates during competition is due to many factors. During competition, there is an increase in speed and intensity of play as well as uncontrolled scenarios. Players exhibit riskier behavior such as aggressive base running, diving for balls, jumping and running into walls, and this is especially noteworthy when considering that the injury rate of contact injuries is approximately five times greater in competitions than practice for shoulders (rate ratio, 5.10; 95% CI, 3.24, 8.02) and elbows (rate ratio, 4.44; 95% CI, 2.36, 8.33) (Table 11). Two of the most common shoulder injuries are anterior dislocation/subluxation and acromioclavicular joint injuries which comprise 18.3% of all injuries (Table 4). Of these, 79.5% occurred during competition, and of those occurring in competition 57.6% were the result of contact with an “apparatus”, another person, or a surface. The majority of competition injuries occurred at first base, the outfield and second base. Although not specified, it may be inferred that the contact may frequently have been the result of a fielder diving for a ball or the interaction between a baserunner and the fielder or the environment. Camp et al.\(^22\) report that among MLB and minor league players shoulder injuries are the third most commonly injured body part with a sliding mechanism during competitions, specifically sliding head first. While not specifying the body region, Dick et al.\(^9\) emphasize the importance of sliding on NCAA injury rates as 13% of all competition related injuries were associated with a sliding

| Table 11. Acute contact injury rates per 10,000 athlete-exposures (AEs) among collegiate baseball players by event type |
|-------------|----------------|----------------|----------------|
|            | Injuries (n) | AEs (n) | Injury Rate* (per 10,000 AEs) | aIRR* (95% CI) |
| Shoulder   |              |         |                              |                |
| Practices  | 71           | 524720  | 0.36                         | Referent       |
| Competitions | 26       | 280021  | 1.65                         | 5.10 (3.24, 8.02) |
| Elbow      |              |         |                              |                |
| Practices  | 14           | 524720  | 0.020                        | Referent       |
| Competitions | 33       | 280021  | 0.088                        | 4.44 (2.36, 8.33) |
| * Adjusted by year and division |
| aIRR = adjusted injury rate ratio |

| Table 12. Acute noncontact injury rates per 10,000 athlete-exposures (AEs) among collegiate baseball players by event type |
|-------------|----------------|----------------|----------------|
|            | Injuries (n) | AEs (n) | Injury Rate* (per 10,000 AEs) | aIRR* (95% CI) |
| Shoulder   |              |         |                              |                |
| Practices  | 91           | 524720  | 1.04                         | Referent       |
| Competitions | 86       | 280021  | 1.86                         | 1.78 (1.32, 2.40) |
| Elbow      |              |         |                              |                |
| Practices  | 63           | 524720  | 0.674                        | Referent       |
| Competitions | 70       | 280021  | 0.17                         | 2.33 (1.68, 3.28) |
| * Adjusted by year and division |
| aIRR = adjusted injury rate ratio |
mechanism. While much has been accomplished in attempt to reduce the number of sliding injuries, such as rule changes and the encouragement to use break-away bases and slide feet first, additional research to investigate their efficacy is necessary.

Interestingly, the injury rate of acute non-contact mechanisms occur almost twice as often during competition compared to practice for shoulders (rate ratio, 1.78; 95% CI, 1.32, 2.40) and elbows (rate ratio, 2.35; 95% CI, 1.68, 3.28) (Table 12). Acute non-contact injuries include those with a specific moment of onset while throwing, pitching or batting. Multiple causative factors may be responsible for this difference. Specific to pitchers, fatigue related changes in throwing mechanics have been demonstrated to occur during\textsuperscript{23} a game and throughout a season.\textsuperscript{23} Such changes in pitching mechanics may predispose the athlete to a shoulder or elbow injury. In contrast among fielders, specific game-related circumstances requiring increased throwing intensity or maximal effort throws across long distances, which occur infrequently, may result in throwing injuries. However, these factors are conjecture and have yet to be supported in the literature. Since 2009 the ISS has collected data specific to the time during the competition that an injury occurs, but there are currently too few cases to analyze. Continued accumulation and analysis of competition data is required to determine the circumstances during a competition that acute-noncontact shoulder and elbow injuries occur.

Shoulder and elbow injury rates are very similar during the preseason and the in-season. Wasserman et al.\textsuperscript{8} reported the same finding for all musculoskeletal injuries. This is in contrast to Dick et al.\textsuperscript{9} who found preseason rates to be significantly greater than the in-season rates for all musculoskeletal injuries. Since the end of the data collection by Dick et al, the Division I baseball preseason has been mandated to be a maximum of three weeks, which is very similar to Division II. During the period of this study, Division III baseball did not have specific guidelines for the championship segment. Given the natural history of overuse disorders, symptom onset from an overuse injury that started during the preseason may not manifest until the regular season. Thus, it would be designated as occurring during the in-season. Injury reports including time specific data such as the month of the season or numbered week of the in-season would permit a clearer assessment of injury causation. Comparison of injury rates during the preseason and in-season across different eras may be inappropriate due to the differences in the duration of exposure and injury acquisition.

Prior to the 2007-2008 season the NCAA provided no specific guidelines regarding the start date of official practice or competitions during the championship segment of collegiate baseball in NCAA Division I. Effective 2007, the NCAA adopted bylaws specifically defining the practice and competition start dates during the championship segment (spring season). The first date that a team was permitted to play its first contest against outside competition was “the Friday in February that is 13 weeks before the Friday immediately preceding Memorial Day”. In addition, preseason practice was not permitted to start prior to February 1.\textsuperscript{24} In 2009, the bylaws were revised to prevent the first contest against outside competition until “the Friday that is 14 weeks before the Friday immediately preceding Memorial Day” with caveats. The start of preseason practice during the championship segment was defined as “the Friday that is three weeks prior to the first permissible contest date”.\textsuperscript{25} As a consequence of the initial revision in 2006, there was concern that the preseason would be shortened and the same number of games would be consolidated into a shorter in-season. Dick et al.\textsuperscript{9}
sensitive to the potential for shoulder and elbow injuries among freshmen and juniors. Extra vigilance should be given to the management of upper extremity stress from throwing and pitching during these times.

Shoulder and elbow injuries have distinct characteristics with regard to return to play (Tables 5 and 10). 52% of shoulder injuries returned to play within two weeks, and 14.5% qualified as a season-ending injury. Of the student-athletes who injured their elbow, 39.9% returned to play in 2 weeks, and the injury ended the season for 28.9% of them. Only 7% of shoulder injuries resulted in surgery. The majority of surgeries addressed superior labral injuries (32.3%), anterior dislocation/subluxation injuries (23.4%), and rotator cuff injuries (21.2%). Over twice as many elbow injuries (17.5%) resulted in surgery, and the most common injuries resulting in surgery was to the UCL (68.7%), capsular sprains (8.8%), olecranon fractures (6.5%) and medial epicondylitis (4.7%). While shoulder injuries have a higher injury rate, elbow injuries have greater morbidity resulting in a greater impact on lost playing time.

LIMITATIONS

Although this is one of the most extensive reports on shoulder and elbow injuries among NCAA student-athletes who play baseball, there are limitations which are inherent to surveillance systems. The participants are volunteer, so they comprise a convenience sample that may not be representative of all NCAA baseball programs. Various information biases must also be acknowledged. Specifically, since the sports medicine staff enters the data without diagnostic criteria, the requirement of physician evaluation or diagnostic testing, there is a risk of misclassification of specific injury types. Due to changes in the ISS methodology that occurred during the 2004-2005 and 2009-2010 academic years, there has been a significant decrease in participants which is exemplified by the large confidence intervals. Given these concerns for the assessment of injury rates, the influence of Division and academic year were statistically controlled, and national estimates that weighted the data based on the variation in school participation between
Divisions and years were also used. Because the ISS does not collect injury data during the non-championship segment of the baseball season, the results only describe injuries that occurred during the championship segment. Injury data from the non-championship segment may provide a more complete description of injury incidence among collegiate baseball student-athletes. Given the high quality control of the data and the good validity of the ISS, it appears to provide valid injury estimates which are, at this time, the most descriptive data collection of NCAA baseball injuries.

CONCLUSION
This study is the first comprehensive analysis of shoulder and elbow injuries in college baseball student-athletes. Although injury rates to these body regions appear to have decreased in the past decade, the morbidity of injuries to the throwing arm, especially the elbow, demands special consideration by sports medicine personnel. Analyzing these trends will lead to a better understanding of possible mechanisms or deficiencies leading to the injuries. Also, consideration of the increased occurrence of injury to freshmen and juniors may lead to prevention programs specific to changes in the workload on their throwing arm. While workload recommendations have been made for youth and adolescent pitchers and catchers to prevent injuries, future research will lead to a better understanding of possible mechanisms or deficiencies leading to the injuries. Also, consideration of the increased occurrence of injury to freshmen and juniors may lead to prevention programs specific to changes in the workload on their throwing arm. While workload recommendations have been made for youth and adolescent pitchers and catchers to prevent injuries, future research may investigate possible throwing recommendations for collegiate student-athletes and all positions.

REFERENCES


ABSTRACT

**Background:** Literature regarding musculocutaneous nerve injuries among the athletic population is scarce, with only several reported clinical cases among baseball and softball pitchers.

**Purpose:** To present a unique case of a musculocutaneous nerve injury to aid in clinician awareness and propose innovative rehabilitation practices that may facilitate improved patient outcomes during recovery.

**Case Description:** A 23-year-old Division 1 NCAA collegiate baseball pitcher presented with vague anterior arm pain following a pre-season game. The athlete described the pain as an “intense stretch” of his right arm that occurred during his last pitch. The initial evaluation identified tenderness over the right distal bicep. All shoulder and elbow orthopedic tests to assess shoulder impingement, labral pathologies, and glenohumeral instability were unremarkable. Increased neural tension was also noted with upper limb neurodynamic testing of the median and ulnar nerves on the right arm compared bilaterally. Electromyography (EMG) testing confirmed a right upper and mid-brachial plexus stretch injury with the primary involvement of the musculocutaneous nerve. Rehabilitation focused on restoring strength deficits and diminishing neural tension. Blood flow restriction (BFR) was introduced on the uninvolved limb to reduce deficits in bicep musculature strength. Once the athlete regained bicep strength and forearm sensation, he was progressed from flat-ground throwing activities to throwing off the mound.

**Outcomes:** A reduction in neural tension during neurodynamic testing of the right arm, improvement of bicep brachii deficits seen between the right and left limbs, and restoration of sensation in the right lateral forearm enabled a progressive return to sport.

**Discussion:** Due to vague reports and inconclusive findings, the initial presentation of musculocutaneous nerve injuries may be mistaken for other conditions such as a biceps brachii strain. Further documentation of this injury and rehabilitation procedures are needed to enhance patient outcomes.

**Key words:** Baseball, blood flow restriction therapy, Movement System, musculocutaneous neuropathy, pitching
BACKGROUND AND PURPOSE
The most common overuse neurological injuries that occur to throwing athletes are thoracic outlet syndrome, cubital tunnel syndrome, suprascapular neuropathy, or quadrilateral space syndrome.1 Among baseball players, musculocutaneous nerve injuries are rare. Peripheral neuropathies related to sports participation account for approximately 6% of all neuropathies.2,3 Injury to the musculocutaneous nerve distal to the innervation of the coracobrachialis has been reported, specifically after heavy exercise.3 Symptoms may include lateral forearm and elbow pain, along with sensory loss over the distal volar forearm.3 Isolated injury to the musculocutaneous nerve is a rare occurrence with few case reports available for review.4-6 The presenting complaints are pain and weakness of the biceps brachii and brachialis muscles as well as numbness/paresthesia in the distal volar forearm.3 Previous cases of musculocutaneous nerve injuries are documented among adolescent, high school, and professional baseball players.4-6 The musculocutaneous nerve originates from cervical levels C5 and C6, converge to make the superior trunk, and ultimately terminates in the musculocutaneous nerve (Figure 1).7,8 The nerve courses from the axilla, through the proximal aspect of the coracobrachialis, and proceeds laterally between the biceps brachii and brachialis to continue throughout the forearm and elbow.7,9 The terminal portion of the musculocutaneous nerve then emerges laterally through the bicep's fascia approximately 4 cm proximal to the antebrachial fossa, providing the sensory function to the lateral forearm becoming the lateral antebrachial cutaneous nerve (LABC).7 The LABC can be injured as a result of compression at this level as a direct consequence of repetitive forceful pronation of the extended elbow, which occurs with throwing.3,7 Treatment strategies in these cases emphasized anti-inflammatories and rest.4-6 Two cases have reported the use of physical therapy interventions; however, specific timelines, goals of treatment, and descriptions of included exercises were not reported.3,6 Reported return to play timelines for the injury varied between 2-7 months.1,4-6 To date, there are no published case reports that describe the use of blood flow restriction (BFR) training as a part of the intervention for musculocutaneous neuropathy in an overhead athlete. The purpose of this care report is to present a unique case of a musculocutaneous nerve injury to aid in clinician awareness and propose innovative rehabilitation practices that may facilitate improved patient outcomes during recovery. The subject gave informed consent to participate in this case report and was informed that de-identified information on his case would be submitted for publication.

CASE DESCRIPTION
A 23-year-old, Division 1 baseball player presented to his athletic trainer complaining of right arm pain after pitching during a pre-season game. The athlete reported feeling an “intense stretch” through his arm after releasing the ball. The athlete also noted general soreness of his biceps musculature after releasing the ball. The athlete did not report any previous history of injury or relevant medical history.
CLINICAL IMPRESSION #1
The athlete’s primary complaint upon initial examination was soreness and weakness of his right biceps musculature. Palpation of the athlete’s right bicep musculature and subclavicular fossa were mildly tender. Internal and external rotation range of motion (ROM) measurements were measured bilaterally in the supine position with the arm elevated to 90 degrees in the scapular plane with the scapula stabilized by the examiner while the arm was passively rotated to end range. Measurements were taken using a digital inclinometer in a vertical direction with the axis of the goniometer aligned with the olecranon process. Glenohumeral internal rotation deficit was calculated by comparing the amount of internal rotation of the throwing arm to that of the non-throwing arm. Shoulder total range of motion (TRM) was calculated by adding the amount of internal and external rotation for each shoulder. Side to side differences in TRM were based on comparing the throwing arm to the non-throwing arm with a negative value indicating lesser TRM for the throwing arm. This method has been described in other reported studies.10–12 Range of motion found during the initial examination for internal rotation (IR), external rotation (ER), and TRM for each arm is detailed in Table 1. The athlete also demonstrated a humeral torsion difference of 29 degrees between his throwing arm and non-throwing arm. A GIRD of 35 degrees was noted in his right shoulder. Humeral retroversion was assessed using an indirect ultrasound technique where the athlete was positioned supine with 90 degrees of shoulder abduction and elbow flexion. The primary examiner then used one hand to apply the diagnostic ultrasound (SonoSite Fujifilm Edge ultrasound system) head over the anterior aspect of the shoulder at the deepest point in the bicipital groove and in the plane of the treatment table. This position was verified with a digital inclinometer and aligned perpendicular with the long axis of the humerus in the frontal plane. The examiners other hand was used to rotate the forearm until the bicipital groove appeared in the center of the ultrasound image and the apexes of the greater and lesser tubercles were parallel to the horizontal plane. Once the greater and lesser tubercles were determined to be parallel, the second examiner used the digital inclinometer to measure the amount of humeral torsion. This method is similar to methods described in previous research studies.13 Previous studies have indicated that humeral torsion contributes significantly to GIRD and increased ER ROM in baseball players.13 Results of manual muscle testing (MMT) during the initial examination are detailed in Table 1. The only deficits that existed were in external rotation and elbow flexion strength, with both rated as a 4/5. Shoulder and elbow orthopedic tests were performed to rule out various conditions, including shoulder impingement, labral pathologies, and glenohumeral instability, which were unremarkable. Table 2 lists the selected orthopedic tests performed and their associated findings. Due to a lack of significant findings upon initial examination, a grade two strain of the biceps brachii was postulated as the initial pathoanatomical diagnosis. The athlete was treated with ice, anti-inflammatory medications, and instructed to rest and refrain from activity for the remainder of the day. The athletic trainer scheduled a follow-up examination for the next day.

Table 1. Initial examination findings. ROM = range of motion, IR = internal rotation, ER = external rotation, TRM = total range of motion, MMT = manual muscle testing, Ext = extension

<table>
<thead>
<tr>
<th>Injured Extremity ROM (R Arm)</th>
<th>Uninjured Extremity ROM (L Arm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR 25 degrees</td>
<td>IR 60 degrees</td>
</tr>
<tr>
<td>ER 105 degrees</td>
<td>ER 75 degrees</td>
</tr>
<tr>
<td>TRM 130 degrees</td>
<td>TRM 135 degrees</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injured Extremity MMT (R Arm)</th>
<th>Uninjured Extremity MMT (L Arm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abduction 5/5</td>
<td>Abduction 5/5</td>
</tr>
<tr>
<td>ER 4/5</td>
<td>ER 4/5</td>
</tr>
<tr>
<td>IR 5/5</td>
<td>IR 5/5</td>
</tr>
<tr>
<td>Elbow Flx. 4/5</td>
<td>Elbow Flx. 4/5</td>
</tr>
<tr>
<td>Elbow Ext. 5/5</td>
<td>Elbow Ext. 5/5</td>
</tr>
</tbody>
</table>
EXAMINATION
One day after the initial injury, decreased sensation was noted along the distribution of the athlete's lateral antebrachial nerve distribution in addition to the decreased strength of the elbow flexors and shoulder external rotators noted in the initial examination. Complete vascular compression occurred when the athlete performed the military brace test for thoracic outlet syndrome. The military brace test is a test for vascular compression of the neurovascular bundle between the first rib and clavicle. While the sensitivity and specificity of military brace test remains unknown, the Halsted maneuver, or the exaggerated military brace test is a similar orthopedic test that has been identified as a sensitive and specific test and is recommended for use in clinical practice. Increased neural tension was also noted with upper limb neurodynamic testing of the median and ulnar nerves. The upper limb neurodynamic tests to identify cervical radiculopathy have been found to have high specificity and low sensitivity with reported sensitivity values ranging from 0.72-0.97 and specificity values ranging from 0.11-0.33. The athlete reported increased numbness and tingling when placed in a position of 90 degrees of shoulder abduction, wrist and finger extension, supination, forearm supination, and elbow extension for median nerve testing. Numbness and tingling were also noted when the athlete was positioned in 90 degrees of abduction, wrist and finger extension, supination, elbow flexion, and external rotation for the ulnar nerve. The findings identified with the military brace test and increased neural tension noted from upper limb neurodynamic testing led clinicians to believe the athlete had suffered a form of neural stretch pathology of the upper extremity. Therefore, the athlete's team physician ordered radiographic imaging, which was unremarkable. Based on these findings, a traction injury of the musculocutaneous nerve injury was suspected, and electromyography (EMG) testing was scheduled to confirm this finding. EMG and nerve conduction velocity studies are the gold standard instruments for diagnosis of neuropathy and are recommended in patients with persistent shoulder pain, atrophy, and weakness with no evidence of a rotator cuff tear.

CLINICAL IMPRESSION #2
Results of the EMG confirmed a stretch injury to the athlete's right upper and mid-brachial plexus with primary involvement of the musculocutaneous nerve. Significant asymmetric prolongation of the right musculocutaneous and axillary motor nerve latencies were seen across the right thoracic outlet and were measured as 6.3 msec and 5.8 msec, respectively. The typical upper limit reference values for the musculocutaneous nerve are 5.6 msec and 5.4 for the axillary nerve. The athlete's physician
confirmed the primary diagnosis of musculocutaneous nerve injury and recommended the athlete begin an oral steroid, refrain from throwing activities, and be started on a comprehensive rehabilitation program focused on regaining strength of the injured limb and decreasing neural sensitivity.

**INTERVENTION**

Restriction from throwing activities continued until the restoration of biceps musculature strength, decreased neural tension, and improved sensation of the lateral cutaneous nerve distribution occurred, which resulted in a loss of approximately 12 weeks of throwing activity. The athlete immediately began a comprehensive rehabilitation program that emphasized involved scapular stabilization, bicep and forearm strengthening, lumbopelvic stabilization, and hip strengthening while waiting for the musculocutaneous nerve to heal. Scapular muscle strengthening and stability exercises were selected to address the athlete's deficit in external rotation strength in the involved limb compared to the uninvolved limb. It is known that the scapular muscles play a vital role in the overhead throwing motion and rehabilitation recommendations in overhead pitchers emphasize targeting scapular stabilizers including shoulder external rotators, supraspinatus, trapezius, serratus anterior, and rhomboid muscles. In this case, the athlete's care team believed that he had an increased head tilt and trunk lean while pitching that increased the athlete's risk for injury. Initially, exercises causing excessive stress on the biceps (e.g., eccentric contractions, abduction) and extension (e.g., biceps curls, dumbbell flies, pull-ups) were avoided to minimize further stretching of the musculocutaneous nerve. Table 3 denotes the exercises introduced within weeks 1-4 of rehabilitation.

BFR was introduced on the uninvolved side and lower extremities utilizing the cross-education theory after four weeks of rehabilitation in an attempt to reduce deficits in biceps strength by enhancing hypertrophy factors and increasing motor fiber recruitment. The parameters of BFR use utilized within this patients care are detailed within Table 4. BFR use is associated with significant hypertrophy and strength gains with loads as low as 30% of 1RM. Therefore, BFR has been a suggested tool, particularly in musculoskeletal rehabilitation in cases where higher strength training loads would not be ideal, including the early stages of the healing process. Previous research has shown that the greatest increase in strength and girth measurement with BFR utilization occurs in the limb where the BFR tourniquet cuff is placed. In one study evaluating the effectiveness of lower extremity BFR training within the limb of cuff placement, the contralateral limb, and controls, found improvements in strength and girth measurements in both the limb of BFR cuff placement and the contralateral limb compared to controls. Strength increases of 8% in knee extension in the non-tourniquet BFR limb, 3% in the control group, and 15% in the BFR limb were seen. Whereas girth increases of 2.3% for thigh circumference in the non-tourniquet BFR limb, .8% for the control, and 3.5% for the BFR limb were seen. While the improvements in girth and strength measures were most significant in the limb of cuff placements, small yet significant changes were still seen in the non-tourniquet limbs compared to controls. This improvement was speculated to occur via the cross-education theory. The cross-education theory postulates that strength training of the uninjured extremity results in bilateral strength increases likely through neural adaptation mechanisms specifically, with eccentric contractions. Strengthening the contralateral upper extremity limb and lower extremities with BFR were initially selected for this athlete due to the concern for adding the tourniquet-cuff on the involved limb during the initial stages of nerve healing. To date, there have been no reports of chronic long-term nerve damage reported in the literature associated with BFR use. However, BFR has been associated with patient reported numbness sensations and possible nerve conduction blockage from external compression which could potentially lead to ischemia. Therefore, the clinicians felt that BFR application in the uninjured upper extremity and lower extremities may be advantageous for the patient to benefit from the potential cross-over effects that have been previously seen. Application of the BFR to the uninjured and each lower extremity was performed with one cuff application at a time. The rehabilitation sessions utilizing BFR application began with the upper extremity followed by lower extremity application with one cuff on one lower extremity at a time.
BFR was induced using KAATSU® belts (Kaatsu training, Sato Sports Plaza Inc., Japan) applied to the athlete's upper thigh for lower extremity strengthening and the upper portion of the humerus just distal to the deltoid for upper limb strengthening. The KAATSU belts contain an electronic air pressure control system that monitors and sets optimal pressure for the individual patient at a rate of 1.3 times higher than resting systolic blood pressure (160-180 mmHg). This is similar to previous studies that have used KAATSU units for BFR strengthening.

Table 3 denotes exercises that were performed within the in weeks 4-8 of rehabilitation. The BFR exercises utilized in weeks 4-8 are detailed within Table 4.

**OUTCOME**

Eight weeks following the athlete's initial injury, a second EMG study revealed a significant reduction of neuropathy findings. Latency measures were recorded as 5.1 msec for the musculocutaneous nerve.
The athlete was allowed to progress through an interval-throwing program prescribed by the athlete’s team physician (Table 5). This protocol was expeditied based on the athlete’s tolerance and tailored towards the athlete’s injury compared to the physician’s typical progression, which usually requires throwing at a specified number of feet for at least a one-week period rather than multiple stage progressions in one week with one day of rest. However, the

<table>
<thead>
<tr>
<th>Rehabilitation Week</th>
<th>BFR Exercises</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Upper extremity</td>
</tr>
<tr>
<td></td>
<td>KAATSU band strapped just below deltoid insertion point</td>
</tr>
<tr>
<td></td>
<td>KAATSU pressure adjusted to 320 mmHg</td>
</tr>
<tr>
<td></td>
<td>3 sets of 30 repetitions (max) performed for each exercise</td>
</tr>
<tr>
<td></td>
<td>30 seconds of rest allowed between each set</td>
</tr>
<tr>
<td></td>
<td>2 minutes of rest allowed between each exercise</td>
</tr>
<tr>
<td></td>
<td>Weight selected for each exercise varied</td>
</tr>
<tr>
<td></td>
<td>Weight was selected by patient to perform exercise to fatigue</td>
</tr>
<tr>
<td></td>
<td>Up to 30 total repetitions</td>
</tr>
<tr>
<td></td>
<td>4 total exercises selected per session</td>
</tr>
<tr>
<td>Lower extremity exercises (2x per week)</td>
<td>KAATSU band strapped to superior thigh</td>
</tr>
<tr>
<td></td>
<td>KAATSU pressure adjusted to 380 mmHg</td>
</tr>
<tr>
<td></td>
<td>3 sets of 30 repetitions (max) performed for each exercise</td>
</tr>
<tr>
<td></td>
<td>30 seconds of rest allowed between each set</td>
</tr>
<tr>
<td></td>
<td>2 minutes of rest allowed between each exercise</td>
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<tr>
<td></td>
<td>Up to 30 total repetitions</td>
</tr>
<tr>
<td></td>
<td>4 total exercises selected per session</td>
</tr>
</tbody>
</table>

**Table 4. Details of BFR interventions**

**Weeks 4-8**

<table>
<thead>
<tr>
<th>Upper extremity example exercises (2x per week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rows (uninjured arm)</td>
</tr>
<tr>
<td>Resisted external rotation (uninjured arm)</td>
</tr>
<tr>
<td>Manually Resisted shoulder Y’s (uninjured arm)</td>
</tr>
<tr>
<td>Bicep curls (uninjured arm)</td>
</tr>
<tr>
<td>Tricep extensions (uninjured arm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower extremity exercises (2x per week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double leg squats on shuttle (bilateral)</td>
</tr>
<tr>
<td>Bulgarian split squat (bilateral)</td>
</tr>
<tr>
<td>Russian deadlifts (bilateral)</td>
</tr>
<tr>
<td>Calf raises (bilateral)</td>
</tr>
<tr>
<td>Reverse lunges (bilateral)</td>
</tr>
</tbody>
</table>

**Weeks 8-12**

<table>
<thead>
<tr>
<th>Upper extremity example exercises (2x per week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rows (bilateral)</td>
</tr>
<tr>
<td>FreeMotion Resisted external rotation (bilateral)</td>
</tr>
<tr>
<td>Manually Resisted shoulder Y’s (bilateral)</td>
</tr>
<tr>
<td>Bicep curls (bilateral)</td>
</tr>
<tr>
<td>Tricep extensions (bilateral)</td>
</tr>
<tr>
<td>Chest fly</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower extremity exercises example exercises (2x per week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee extensions (bilateral)</td>
</tr>
<tr>
<td>Double leg squats on shuttle (bilateral)</td>
</tr>
<tr>
<td>Hamstring curls (bilateral)</td>
</tr>
<tr>
<td>Bulgarian split squat (bilateral)</td>
</tr>
<tr>
<td>Russian deadlifts (bilateral)</td>
</tr>
<tr>
<td>Calf raises (bilateral)</td>
</tr>
<tr>
<td>Reverse lunges (bilateral)</td>
</tr>
<tr>
<td>Side lunges (bilateral)</td>
</tr>
</tbody>
</table>

and 4.1 for the axillary nerves, both of which are within regular latency references. However, while improvements were seen in reduced nerve latency and biceps brachii strength, a deficit in bicep brachii strength continued to be present with manual muscle testing being scored as 4+/5. The biceps brachii has a primary role as a stabilizer for the elbow and shoulder throughout the acceleration phase of pitching.24 Due to his diminished neurotension findings,
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continued resolution of neurotension findings and increased bicep brachii strength to 4+/5 on MMT. Therefore, the athlete was allowed to continue to progress in his interval-throwing program 12 weeks after the initial injury and was cleared to begin throwing off the mound by his team physician.

DISCUSSION

Neuropathies account for 2% of all causes of pain and weakness of the shoulder.1 The initial presentation of peripheral nerve injuries may be mistaken for other conditions such as muscle strains, rotator cuff tears, or other neurologic conditions such as cervical radiculopathy and may further complicate definitive diagnoses.1 Literature regarding the management and recovery timelines of musculocutaneous nerve injuries among baseball players is limited with time loss reports ranging from two to six months.4–6 Healing rates for peripheral nerves are highly variable, ranging from weeks to years, depending on the location of neural compromise and classification of neuron degeneration.26,27 Proximal neuron segments may heal at a rate of 2-3mm/day, whereas distal regeneration may occur at a slower rate of 1-2mm/day.26 Peripheral nerve traction injuries often result in neuropraxia which is classified as focal demyelination without axon or connective tissue damage and reduction in conduction velocity.28 From a biomechanical perspective, overstretching of the musculocutaneous nerve may occur in the pitching motion at the time of ball release due to the traction force placed through the arm as it attempts to decelerate thus placing excessive stress on the anterior shoulder including increased stress through the bicep musculature.29,30

Table 5. Interval Throwing Program

<table>
<thead>
<tr>
<th>Rehabilitation Week</th>
<th>Example Exercises</th>
</tr>
</thead>
</table>
| Weeks 1             | Day 1: 1 set of 25 throws at 90 feet*  
                    Day 2: 2 sets of 25 throws at 90 feet*  
                    Day 3: 3 sets of 25 throws at 90 feet*  
                    **At least one day of rest between throwing days |
| Weeks 2             | Day 1: 1 set of 25 throws at 105 feet*  
                    Day 2: 2 set of 25 throws at 105 feet*  
                    Day 3: 3 sets of 25 throws at 105 feet*  
                    *At least one day of rest between throwing days |
| Weeks 3             | Day 1: 1 set of 25 throws at 120 feet**  
                    Day 2: 2 sets of 25 throws at 120 feet* (hat drills)*  
                    1 set of 25 throws from the mound  
                    *At least one day of rest between throwing days  
                    **Required physician clearance to begin this level |
| Weeks 4             | Day 1: 3 sets of 25 throws at 120 feet*  
                    Day 2: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 25 throws from the mound  
                    Day 3: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 25 throws from the mound  
                    *At least one day of rest between throwing days |
| Weeks 5             | Day 1: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 25 throws from the mound  
                    Day 2: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 25 throws from the mound  
                    Day 3: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 35 throws from the mound  
                    Day 4: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 35 throws from the mound  
                    *At least one day of rest between throwing days |
| Weeks 6             | Day 1: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 35 throws from the mound  
                    Day 2: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 35 throws from the mound  
                    Day 3: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 40 throws from the mound  
                    Day 4: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 40 throws from the mound |
| Weeks 7             | Day 1: 1 set of 25 throws at 120 feet (hat drills)*  
                    1 set of 40 throws from the mound  
                    Day 2: Bull pen (10 minutes)**  
                    **End of formal interval throwing program |

*the athlete was prohibited from mound throwing until improvements in biceps strength were improved to a 4+/5 on MMT or better. BFR rehabilitation sessions continued to be completed two days per week in-between days of progressive resistive exercises. At this time, BFR was applied to the involved limb due to diminished neurotension signs and decreased concern for the potential adverse neural effects that may occur with BFR use.21 Exercises performed during weeks 8-12 of rehabilitation are outlined in Table 3. While the athlete never regained full sensation of his lateral cutaneous nerve, he did experience
CONCLUSIONS

This case report is the first to detail a rehabilitation protocol for treatment of a musculocutaneous nerve injury in a collegiate pitcher, which may be a beneficial reference for clinicians who may encounter this pathology. Further research on the efficacy of BFR is needed, especially for upper extremity diagnoses as most of the literature is limited to lower extremity outcomes. Furthermore, the athlete was eventually able to return to pitching and full training without the onset of symptoms or recurrence of neurotension signs. Clinicians are advised to use their judgment as to whether or not the inclusion of BFR in the rehabilitation protocol of an injury such as this is beneficial based on the time and cost associated with this rehabilitation tool. Additionally, further reporting of clinical cases of musculocutaneous nerve injuries in athletic populations is needed in order to compare varied patient rehabilitation strategies and outcomes for this injury.

REFERENCES


ABSTRACT

Background and Purpose: Proximal hamstring tendinopathy is a chronic, overuse condition that commonly develops in athletes. Eccentric exercise has been widely accepted in the clinic as the treatment of choice for the management of tendinopathies. However, this form of treatment has seldom been compared to other forms of load-based management for hamstring tendinopathies. Heavy slow resistance training, which consists of both concentric and eccentric phases, increases the loading time experienced by the tendon compared to eccentric only exercises. Heavy slow resistance training has achieved positive clinical results in the management of Achilles and patellar tendinopathy.

Purpose: The purpose of this case report is to describe the outcomes of a powerlifter with proximal hamstring tendinopathy who responded favorably to a heavy slow resistance biased rehabilitation program after traditional, conservative management failed to alleviate symptoms.

Case Description: A 31-year-old male competitive powerlifter was seen in physical therapy for the management of proximal hamstring tendinopathy. The subject had experienced long duration pain localized at the ischial tuberosity combined with hip weakness that limited his ability to lift weight and sit for longer than 30 minutes. Treatment included a 12-week heavy slow resistance program with the focus of increasing load intensity.

Outcomes: Numeric pain-rating scale was assessed at baseline, after a 12-week heavy slow resistance protocol, and 12 months post protocol. Within four weeks of starting the heavy slow resistance program, the subject noted a meaningful decrease in pain. The subject experienced clinically important improvements in numeric pain-rating scale immediately after the protocol and these improvements remained 12 months after completing the protocol. The subject was able to return to competitive powerlifting after the 12-week program.

Discussion: A meaningful change in pain occurred within four weeks of starting the program and continued improvement throughout the remainder of the 12 weeks with outcomes maintained 12 months after completing the program suggests that increasing the loading strategy with a heavy slow resistance program was helpful for this subject.

Level of Evidence: 4

Keywords: Hamstring, heavy slow resistance, eccentrics, tendinopathy
BACKGROUND AND PURPOSE
Proximal hamstring tendinopathy (PHT) is a chronic, overuse condition that develops as a result of repetitive mechanical loading at the proximal hamstring tendon. Tendinopathic changes are attributed to a combination of tensile loading and compressive forces applied to the common hamstring tendon near the attachment at the ischial tuberosity during movements that require the hamstrings to contract or lengthen while in hip flexion and adduction. PHT is most commonly diagnosed in sagittal plane dominant athletes such as middle and long-distance runners or in individuals who routinely perform exercises and activities that contribute to tensile and compressive loading of the proximal hamstring tendon. Exercises and activities thought to increase the tensile and compressive load at the proximal tendon insertion include those involving hip-flexion dominant movements such as squatting, lunging, leaning forward, stairs, uphill running, and sitting for long periods.

The primary subjective complaint of PHT is well-localized pain of insidious onset at the ischial tuberosity that is exacerbated with sitting, driving, and activities requiring end-range hip flexion. PHT is often diagnosed clinically based on a detailed history and physical examination. Traditional treatment strategies of PHT are almost always conservative and focus on the progressive loading of the tendon, within a pain-monitoring framework, in order to reduce pain, restore function, and prevent reinjury. Eccentric exercise, which involves isolated, slow-lengthening muscle contractions, has been widely accepted as the treatment of choice for the management of tendinopathies. However, recent evidence suggests that not all patients with tendinopathy respond to this intervention. In one study, up to 45% of patients with Achilles tendinopathy did not improve with an eccentric exercise regimen. Mechanisms underlying the effectiveness of eccentric training alone are poorly understood and the treatment has seldom been compared to other forms of load-based management. A recent systematic review reported that when load is normalized in patients with patellar and Achilles tendinopathy, eccentric loading does not lead to greater muscle-tendon recruitment than concentric and isometric contractions when external load and speed are constant. This suggests that load intensity rather than contraction type may be the driving stimulus. Therefore, it is not entirely clear why avoiding the concentric component should produce more favorable outcomes.

Heavy slow resistance (HSR) training, which contains both concentric and eccentric phases, increases the loading time, or time under tension, experienced by the tendon compared to eccentric only training. The focus, with HSR training, is to perform slow, fatiguing, progressive resistance exercise with both concentric and eccentric components. Increasing a tendons time under tension leads to greater tendon adaptation. A recent randomized clinical trial compared HSR with traditional eccentric only exercise in the management of Achilles and patellar tendinopathy. Both the HSR and eccentric only groups yielded positive clinical results at 12- and 52-weeks post-treatment, however, the HSR group reported greater treatment satisfaction after 12-weeks due to the decreased time required to complete the HSR training regimen. Research has yet to examine the effectiveness of HSR training on the PHT or on upper extremity tendinopathies such as rotator cuff tendinopathies, common flexor tendinopathy (i.e. golfer’s elbow), and common extensor tendinopathy (i.e. tennis elbow).

The purpose of this case report is to describe the outcomes of a powerlifter with PHT who responded favorably to a HSR biased rehabilitation program after traditional, conservative management failed to alleviate symptoms.

CASE DESCRIPTION
The patient was seen in physical therapy for the management of left proximal hamstring tendinopathy. The subject provided clinical information for this case presentation and signed a written form of consent.

SUBJECT HISTORY AND SYSTEMS REVIEW
The subject was a 31-year-old male competitive powerlifter that was referred to physical therapy with a differential medical diagnosis of left PHT. The subject had a history of symptomatic bilateral femoro-acetabular impingement (FAI), with the presence of a cam deformity that was confirmed with imaging. The subject had undergone a bilateral hip femoro-plasty and labral repair five years prior, which resolved his anterior groin pain associated with this
condition. The subject was otherwise healthy and did not report any other outstanding past medical history. The subject stated that prior to seeking recent treatment for his current condition, his sports medicine physician referred him to physical therapy at a different facility with a prescription labeling his health condition as PHT. This treatment included static and dynamic hamstring stretching, hamstring soft tissue mobilization (STM), dry-needling, general hamstring strengthening exercises, and exercises that eccentrically loaded his hamstrings using body weight or manual resistance applied by the treating therapist. The subject self-discharged from physical therapy after nine visits due to lack of progress. Approximately 60 days after discharging from physical therapy, the subject discussed additional treatment options with his referring physician. The subject opted to receive a left proximal hamstring tendon tenotomy and platelet-rich plasma (PRP) injection. After the PRP procedure was performed without complication, the subject was referred to a different physical therapy clinic for treatment of his left PHT. Treatment at this facility included left hip joint self-mobilizations, active release techniques at the ischial tuberosity, proximal hamstring cupping, and free weight exercises that included kettlebell Romanian deadlifts and modified trap bar deadlifts. After four visits, the subject did not see any improvement of symptoms and self-discharged from physical therapy again due to a continued lack of progress.

When asked about his current condition, the subject stated that symptoms consistent with his left PHT were still present. The subject stated that he experienced an insidious onset of pain localized at the ischial tuberosity approximately two years prior but was able to continue powerlifting submaximally with intermittent symptoms. His one repetition maximum (1RM) lifts for the back squat and deadlift were 400 pounds and 475 pounds, respectively. The subject’s primary complaint was pain that worsened with activities that required hip flexion while maintaining a neutral spine such as deadlifting, squatting, and lifting objects off of the floor. His previous physical therapists advised him to keep loaded hip extension movements during weight lifting pain free by limiting load and reducing range of motion, which resolved some of his symptoms; however, the subject continued to have pain with prolonged sitting and driving (>30 minutes). The subject rated his pain as 8/10 with prolonged sitting and driving. This affected the subject’s ability to meet the expectations of his job. The subject’s primary goal was to decrease pain with functional activities such as sitting and return to competitive powerlifting.

**CLINICAL IMPRESSION #1**

This subject appeared to be a good candidate for an alternative form of load-based management due to his history of unsuccessful physical therapy utilizing traditional, conservative treatment and ongoing subjective complaints consistent with PHT. Specifically, HSR training was considered due to its increased intensity and tendon time under tension, as compared to his previous rehabilitation loading strategy. Greater tendon time under tension has been shown to cause changes in fibril morphology and creation of new fibrils, altering the pathological tendon towards normal morphology. A physical examination to include standing posture, palpation, strength, ROM, special testing, functional testing consisting of visual appraisal of weight lifting movements, and self-report outcome measures was warranted. Standing posture was performed to determine if there were any flagrant bony malalignments or soft tissue asymmetries which may have developed over his two-year history of this condition. Palpation, strength, and ROM were performed to confirm PHT as the primary diagnosis. Special tests were performed to rule out other possible diagnoses. Functional testing was performed to determine if movement faults or asymmetries were present and to better understand his pain characteristics and determine prognostic factors that may suggest appropriateness for the intervention approach.

**EXAMINATION**

A thorough regional and global physical examination was performed on the subject by a licensed physical therapist with notable findings presented in Table 1. A postural assessment, performed in a standing position, revealed the iliac crest was elevated on the left side relative to the right side and the subject stood with a posterior pelvic tilt. While in a prone position, the subject reported mild tenderness to palpation over the left proximal hamstring tendon and its attachment at the ischial tuberosity. There was no
apparent swelling, redness, or additional palpatory findings associated with this area.

Left hip joint active and passive ROM and strength measurements were collected in their respected standardized testing positions.\textsuperscript{10,11} Left hip extension and external rotation ROMs were limited. Hip flexion, extension, adduction, and abduction manual muscle tests were performed, with weakness noted in all planes of movement and pain upon resistance during testing of the extensors and adductors. Special tests performed on the left hip included the flexion-abduction-external rotation (FABER), flexion-adduction-internal rotation (FADIR), and hip scour tests, which were all negative.\textsuperscript{12} The left sacroiliac joint was assessed using Gaenslen's provocation test, which was negative.\textsuperscript{12}

Muscle extensibility on the left extremity was assessed using the Thomas test, Ober's test, and the 90-90 hamstring length test, which were all negative.\textsuperscript{5} Although the 90-90 hamstring length test did show normal hamstring extensibility, it did reproduce the subject's concordant sign. The spine and possible sciatic nerve involvement was assessed using the quadrant test with overpressure at end-ranges and straight leg raise (SLR) test, which were both negative.\textsuperscript{12} When considering reliability, sensitivity, specificity, and likelihood ratios, evidence moderately supports the use of SLR and FABER tests; minimally supports or does not support the use of Gaenslen's provocation, FADIR, and Thomas tests; and the quadrant and hip scour tests have not been researched sufficiently to determine their value.\textsuperscript{13}

Neurological testing was unremarkable for light touch sensation and deep tendon reflexes of the patellar and Achilles tendons.\textsuperscript{12} An observational gait-analysis was performed. No symptoms were reproduced with walking and no deviations were noted. The subject performed an unloaded single-leg Romanian deadlift (RDL) on the left extremity, with concordant pain increasing from a 1/10 to 5/10.

Self-report outcome measures included the Lower Extremity Functional Scale (LEFS), which is a valid and reliable measure for assessing functional impairments resulting from lower extremity musculoskeletal conditions.\textsuperscript{14} The subject scored 65/80 points, indicating a mild degree of functional limitations.

**CLINICAL IMPRESSION #2**

A number of pathologies can refer pain to the posterior thigh region, including piriformis syndrome, ischiogluteal bursitis, ischiofemoral impingement, lumbar disc or facet dysfunction, sacroiliac joint dysfunction, and spondylogenic lesions. These pathologies were unlikely due to findings in the examination such as pain with resisted motion into hip extension and adduction, concordant sign when the PHT is subjected to tensile and compressive loading during the single-leg RDL, tenderness to palpation over the ischial tuberosity, and negative special tests. Slight hip weakness was documented in all cardinal planes, with pain noted with resisted hip extension and adduction. This slight weakness was unlikely to have been “true” muscular weaknesses, considering the subject's experience with resistance training and 1RMs in the deadlift and back squat being 475 pounds and 400 pounds, respectively. Therefore, this slight weakness may have been a consequence of pain. His exam findings suggest that the dysfunction was contractile in nature and involved the proximal hamstring tendon.

Thus, the working clinical diagnosis was PHT. Based on these findings, it was determined that the subject would be a good candidate for HSR training due to its tendon loading properties. It was determined that a functional outcome measure would include the NPRS, which would be assessed for prolonged sitting and during weight lifting at baseline, after a 12-week HSR protocol, and 12-month post HSR protocol. Prolonged sitting and weight lifting tolerance were monitor throughout the intervention as

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Physical Exam Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Localized L buttock pain, ranging from 0-8/10</td>
<td>MMT results: L hip flexors (4/5), abductors (4-5), adductors (4-5), extensors (4-5)</td>
</tr>
<tr>
<td>Pain worsens with sitting, deadlifting, driving, squatting, and bending over to pick up objects from floor</td>
<td>Pain with resisted hip extension and adduction during MMT</td>
</tr>
<tr>
<td>Decreased AROM L hip: extension 7°, ER 10°</td>
<td>90-90 hamstring passive length test on L revealed normal extensibility, but provoked pain</td>
</tr>
<tr>
<td>Tenderness to palpation at L proximal hamstring tendon and ischial tuberosity</td>
<td>In standing, iliac crest was elevated on L relative to R side and posterior pelvic tilt was noted</td>
</tr>
</tbody>
</table>

Table 1. Summary of Symptoms and Physical Exam Findings.
these were his goals for physical therapy and these tasks easily reproduced his concordant sign. It was hypothesized that the subject would have clinically important improvements in sitting and weight lifting if HSR training were to be successful.

**INTERVENTION**

Due to the history of unsuccessful PT, the subject chose to perform this program independently as a home exercise program under the supervision of the overseeing therapist to avoid having to go into the clinic for scheduled treatment sessions. The subject performed three weekly sessions, each of which consisted of the choice of two bilateral exercises, which included: low bar back squats, sumo deadlifts, Romanian deadlifts, conventional deadlifts, trap bar deadlifts, good mornings, loaded barbell hip thrusts, and lying leg curl and the choice of one unilateral exercise, which included: single-leg Romanian deadlifts with dumbbells, single-leg hamstring curls, and reverse dumbbell lunges. These exercises were selected, in collaboration with the subject, due to their reproducibility of the concordant sign and the subject was familiar with these movements. The subject was instructed to spend three seconds completing each of the concentric and eccentric phases, respectively (i.e. 6 s/repetition).

The repetitions in reserve (RIR)-based rating of perceived exertion (RPE) scale for resistance training was used as a method to assign daily training load and intensity and aid in session-to-session and weekly load progression. The RIR-based RPE scale provides a valid measure of resistance training intensity based on how many repetitions are remaining at the completion of a set.\(^{15}\) This approach accounts for individual differences and ensures that the appropriate load is applied for each repetition, while reducing the risk for failure.\(^{16}\) Minimizing the risk for failure with this RIR scale increased the safety of the program and helped ensure the subject would be able to complete the 12-week HSR program. Some of the exercises (eg. back squat) required a spotter if the RIR was less than one and may have led to injury if this program routinely had this subject lifting to failure. The RIR used also ensured the intensity could be maintained while load was increased throughout the 12-week program. The subject initially performed all resistance exercises at a RPE of 7 (3 RIR) and progressed to a RPE of 9 (1 RIR) as the subject became more accustomed to the protocol in order to accommodate for muscular adaptation. The subject was told that moderate pain during exercises was acceptable and encouraged, but pain and discomfort was not to increase following cessation of training. A RPE of 7-9 was used to ensure adequate load intensity during the progressive loading of the tendon during these resistance exercises. These recommendations on pain were based on prior research on HSR,\(^{6}\) Achilles tendinopathies,\(^{17,18}\) and patellar tendinopathies.\(^{19,20}\) The subject's HSR protocol is presented in Table 2. The subject's detailed exercise program is presented in Appendix 1. Load intensities based on 1 RM are presented in Table 3. No other co-interventions were received or performed by the subject.

The subject chose to perform this plan of care independently at home. The physical therapist followed up with the subject via email, phone, or text every two weeks during the 12-week HSR program. These follow up conversations focused on monitoring program compliance; collecting data related to pain, sitting tolerance, and weight lifting tolerance; and offering encouragement.

**OUTCOME**

Following a 12-week independent rehabilitation program utilizing HSR training, the subject showed functional improvement and was able to return to competitive powerlifting with minimal pain. Additionally, prolonged sitting and driving was no longer an aggravating activity for the subject. Numeric

---

**Table 2. Outline of the Heavy Slow Resistance (HSR) Training Protocol and Instructions.**

<table>
<thead>
<tr>
<th>Set</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetitions</td>
<td>6-15</td>
</tr>
<tr>
<td>Pacing/tempo</td>
<td>3 seconds for eccentric phase, 3 seconds for concentric phase</td>
</tr>
<tr>
<td>Pain allowance</td>
<td>Exercises should elicit moderate but not disabling pain</td>
</tr>
<tr>
<td>Load</td>
<td>Keep RPE in a range of 7 (3 RIR)- 9 (1 RIR); increase load or repetitions to maintain this range as tolerated</td>
</tr>
<tr>
<td>Frequency</td>
<td>3x/week</td>
</tr>
<tr>
<td>Movement type</td>
<td>Each workout included: 2 bilateral exercises and 1 unilateral exercise. Subject was given a choice between these exercises: Bilateral – back squats, sumo deadlifts, conventional deadlifts, Romanian deadlifts, goodmornings, barbell hip thrust, prone hamstring curl Unilateral – single leg Romanian deadlifts, single leg hamstrings curls, reverse lunges</td>
</tr>
</tbody>
</table>

Abbreviations: repetitions in reserve (RIR), rating of perceived exertion (RPE)
lifting) with previous interventions consisting of hamstring stretching, soft tissue and joint mobilization, dry-needling, low load and intensity hamstring strengthening, eccentric exercises using the subject's body weight, cupping, and PRP injection. The subject reported minimal short-term effects and no long-lasting effects to the aforementioned interventions.22,23,24 There is evidence that tendons are highly responsive to diverse active loading strategies while there is minimal evidence to support the efficacy of the use of manual therapy for the management of tendinopathy.25

Because previous physical therapy and medical interventions were not effective for this subject, a HSR program was proposed in an attempt to increase the load intensity of the rehab program, as well as the PHT's time under tension, in order to reduce pain and restore function. Within four weeks of starting this HSR program, the subject noted a meaningful decrease in pain, which help to provide motivation to remain compliant with the remainder of the protocol. The subject experienced clinically important improvements in NPRS immediately after the HSR protocol and these improvements remained one year after completing the HSR protocol. NPRS decreased 6 points during lower body weight lifting exercises and 7 points during prolonged sitting.

DISCUSSION
This case report describes the clinical reasoning and the physical therapy management of a subject with chronic PHT who was not able to return to his prior level of functioning (prolonged sitting and weight lifting) with previous interventions consisting of hamstring stretching, soft tissue and joint mobilization, dry-needling, low load and intensity hamstring strengthening, eccentric exercises using the subject's body weight, cupping, and PRP injection. The subject reported minimal short-term effects and no long-lasting effects to the aforementioned interventions. The primary goal in tendinopathy rehabilitation is improving the capacity of the tendon to manage load. There is evidence that tendons are highly responsive to diverse active loading strategies while there is minimal evidence to support the efficacy of the use of manual therapy for the management of tendinopathy.25

A subject management timeline with numeric pain-rating scale outcomes are depicted in Figure 1. The subject was instructed to continue this program without reservation and follow-up with the treating therapist if symptoms returned. Outcomes for the subject are summarized in Table 4.

**Table 3. Load Intensities Based on 1RM**

<table>
<thead>
<tr>
<th>Start of HSR Program</th>
<th>Week 6 of HSR Program</th>
<th>Peak of HSR Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Squat: 95% (24% of 1RM)</td>
<td>Back Squat: 25% (66% of 1RM)</td>
<td>Back Squat: 35% (91% of 1RM)</td>
</tr>
<tr>
<td>Deadlift: 115% (24% of 1RM)</td>
<td>Deadlift: 25% (49% of 1RM)</td>
<td>Deadlift: 40% (85% of 1RM)</td>
</tr>
</tbody>
</table>

Abbreviations: 1RM = one repetition maximum, HSR = heavy-slow resistance

**Table 4. Visual Analogue Scale and Patient’s Functional Goals**

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>Initial Assessment</th>
<th>12 Weeks</th>
<th>12 Month Follow Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Analogue Scale</td>
<td>8/10</td>
<td>2/10</td>
<td>2/10</td>
</tr>
<tr>
<td>Self-Reported Function</td>
<td>Unable to sit &gt;30 minutes due to pain</td>
<td>2/10 with sitting &gt;30 minutes</td>
<td>2/10 with sitting &gt;60 minutes</td>
</tr>
<tr>
<td></td>
<td>Pain caused patient to discontinue performing loaded hip extension movements during weightlifting</td>
<td>1/10 with weight lifting</td>
<td>1/10 with weight lifting</td>
</tr>
</tbody>
</table>

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Figure 1. Patient management timeline from February 2016 to June 2019 with related numeric pain-rating scale outcomes before, during, and after novel treatment. Abbreviations: proximal hamstring tendinopathy (PHT), plasma-rich platelet (PRP), heavy-slow resistance (HSR)
demonstrate a favorable response to a HSR program in a subject with PHT. Relevant in this case is the unique anatomical features of the PHT that differ from the Achilles and patellar tendons. The PHT has thick soft tissue coverage as well a close location to the sciatic nerve. Anatomically, the semitendinosis, semimembranosus, and long head of biceps femoris tendons insert on the ischial tuberosity, with the inferior border of the gluteus maximus and the sciatic nerve having close proximity to the ischial tuberosity and proximal hamstring tendons. Due to these anatomical features, the general recommendations for treatment of tendinopathies have been questioned in terms of effectiveness and safety for PHT. This case report supports the notion that load intensity rather than contraction type is the optimal stimulus for the management of tendinopathies, including PHT.

This case report has multiple limitations. First, the subject received many therapeutic exercise interventions prior to initiating the HSR program and some of the HSR program movements were very similar to the previous exercises, which may have impacted his overall success. Nevertheless, as the exercise program was unsuccessful as previously implemented, it seems that increasing the intensity of the load and PHT's time under tension via a HSR program may have led to better outcomes. Second, the subject also received a PRP injection eight weeks prior to initiating the HSR program. While there is evidence suggesting that PRP for the treatment of PHT is ineffective, there is also evidence supporting the use of PRP injections to manage PHT especially after failed conservative care. It should also be acknowledged that some investigators claim that the best clinical benefit of PRP injections occurs in the long-term period (>12 months) which was included in the time span of this case report.

As demonstrated in Appendix 1, the subject was not fully compliant with performing his HSR program three times each week or performing three exercises per training session. This suggests that there may have been benefit from the HSR protocol even with a lower training frequency than was intended. Previous research comparing HSR and eccentric only protocols noticed improved satisfaction with the HSR group due to the decreased time required to complete the HSR training program as compare to an eccentric only protocol. The subject of this case report responded with a lower frequency than previously discussed. Due to previously reported benefits seen with the lower frequency HSR protocol, future studies designed to look at the effect of frequency on outcomes are warranted.

Previous research on HSR has shown positive clinical results in the management of Achilles and patellar tendinopathies. This case report is the first study to demonstrate a favorable response to a HSR program in a subject with PHT. Relevant in this case is the unique anatomical features of the PHT that differ from the Achilles and patellar tendons. The PHT has thick soft tissue coverage as well a close location to the sciatic nerve. Anatomically, the semitendinosis, semimembranosus, and long head of biceps femoris tendons insert on the ischial tuberosity, with the inferior border of the gluteus maximus and the sciatic nerve having close proximity to the ischial tuberosity and proximal hamstring tendons. Due to these anatomical features, the general recommendations for treatment of tendinopathies have been questioned in terms of effectiveness and safety for PHT. This case report supports the notion that load intensity rather than contraction type is the optimal stimulus for the management of tendinopathies, including PHT.

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Third, the natural recovery of PHT may have impacted the results for this subject. Although the time to full recovery for PHT is normally one to three months, the time to full recovery from tendon injuries can take more than a year, especially in patients that fail conservative treatment. Finally, in this case report, the clinician and the subject were not able to be blinded to the treatment or outcomes, which could have biased the results.

As the results of a single case report cannot be generalized to other patients, additional research is needed.
to determine the effectiveness of this protocol in a greater number of subjects. Performing a case series or eventually designing a randomized controlled trial that uses a greater number of participants, utilizes a control group, and blinds researchers would be helpful in determining the effectiveness of HSR training in the management of PHT.

CONCLUSION
This case report describes the management of a subject with chronic PHT. Physical therapy intervention consisted of an independent 12-week HSR protocol. The results of this case report indicate that load intensity rather than contraction type is the optimal stimulus for the management of PHT. The subject experienced clinically meaningful changes in pain and functional status at 12 weeks, and these changes remained at the 12 month follow up.

REFERENCES


**APPENDIX 1. HEAVY SLOW RESISTANCE TRAINING EXERCISE PROGRESSION OVER 12 WEEKS**

<table>
<thead>
<tr>
<th>Week</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BS: 950 x15, Barbell Hip Thrust: 55# x12, 650 x12, Standing SL Curl: 100 x12</td>
<td>BS: 1350 x15, 1550 x2 x15, 1550 x3 x10, Standing SL Curl: 150 x10</td>
<td>BS: 1650 x15, 1650 x2 x15, Barbell Hip Thrust: 650 x2 x15, 500 x12, Lying Leg Curl: 300 x15, 400 x2</td>
</tr>
<tr>
<td>2</td>
<td>Traps Bar DL: 220 x12, Barbell Hip Thrust: 65# x12, Lying Leg Curl: 50# x12, 550 x12</td>
<td>BS: 1850 x12, DB Lunge: 200 x12, Standing SL Curl: 100 x10, 180 x12</td>
<td>BS: 1850 x12, DB Lunge: 200 x12, Standing SL Curl: 100 x12</td>
</tr>
<tr>
<td>3</td>
<td>BS: 1850 x12, 2650 x2 x12, Lying Leg Curl: 45# x12, 500 x12, SL Romanian DL: 60 x15</td>
<td>BS: 2050 x12, Romanian DL: 65# x12, Lying SL Curl: 150 x12, 200 x12</td>
<td>BS: 2050 x12, Romanian DL: 65# x12, Lying SL Curl: 100 x12</td>
</tr>
<tr>
<td>4</td>
<td>BS: 2250 x10, Romanian DL: 1550 x10, 1550 x2 x10, Lying SL Curl: 200 x10, 250 x10</td>
<td>BS: 2250 x10, 2500 x2 x10, 1550 x2 x10, Reverse DB Lunge: 200 x10, 250 x10</td>
<td>BS: 2250 x10, 2500 x2 x10, 1550 x2 x10, Reverse DB Lunge: 200 x10, 250 x10</td>
</tr>
<tr>
<td>5</td>
<td>BS: 2550 x4 x10, Romanian DL: 1750 x10, 1850 x2 x10, Reverse DB Lunge: 250 x3 x10</td>
<td>BS: 2550 x10, 2650 x3 x10, 1550 x2 x10, 1600 x10</td>
<td>BS: 2550 x10, 2650 x3 x10, 1550 x2 x10, Reverse DB Lunge: 250 x3 x10</td>
</tr>
<tr>
<td>6</td>
<td>BS: 2650 x8, 2750 x8, 2850 x8, DL: 2050 x8, 2250 x8, 2350 x8, Reverse DB Lunge: 35# x3 x8</td>
<td>Sumo DL: 2650 x8, 3150 x8, 2650 x3 x8, Lying SL Curl: 250 x3 x8</td>
<td>BS: 2950 x8, 3150 x8, SL Romanian DL: 3250 x8, 2950 x8, Lying SL Curl: 250 x3 x8, 500 x2 x8</td>
</tr>
<tr>
<td>7</td>
<td>BS: 2550 x8, 3150 x8, 3150 x7</td>
<td>SL Romanian DL: 2550 x8, 2450 x8, Lying SL Curl: 45# x8, 500 x2 x8</td>
<td>BS: 3200 x8, 3250 x2 x7, 2850 x8, 2550 x8, SL Romanian DL: 350 x3 x8</td>
</tr>
<tr>
<td>8</td>
<td>BS: 3150 x8, 3250 x2 x8, 3300 x8, 3350 x8, Romanian DL: 2550 x8, 2650 x2 x8, SL Seated Leg Curl: 40# x8, 500 x2 x8</td>
<td>Sumo DL: 3350 x8, 3550 x8, 3750 x8, 3550 x8</td>
<td>BS: 3150 x8, 3250 x6, 3250 x2 x5</td>
</tr>
<tr>
<td>9</td>
<td>BS: 3250 x8, 3350 x7, 3350 x8, Romanian DL: 2600 x8, 2630 x2 x8, 2600 x2 x8, 450 x8, 450 x8, Reverse DB Lunge: 40# x7</td>
<td>Sumo DL: 3350 x8, 3550 x8, 3750 x8, 3550 x8</td>
<td>BS: 3150 x8, 3200 x6, 3250 x2 x5</td>
</tr>
<tr>
<td>10</td>
<td>BS: 2850 x8, 2950 x8, 3150 x6, 2450 x8, 2550 x8, 2650 x8, SL Seated Leg Curl: 40# x6, 450 x6, 450 x8, 500 x2 x8</td>
<td>Sumo DL: 4050 x8, 4050 x6, 4050 x8</td>
<td>BS: 3150 x8, 3550 x6, 3450 x6, 2550 x8, 2500 x8, SL Romanian DL: 350 x3 x8</td>
</tr>
<tr>
<td>11</td>
<td>BS: 3550 x6, 3450 x6, 3350 x6, Romanian DL: 2650 x3 x6, SL Hip Thrust: 45# x8, 450 x8, 450 x2 x10</td>
<td>BS: 3150 x6, 3250 x6, 3650 x5 x6, 3500 x5 x6, 3500 x5 x6, 3500 x5 x6</td>
<td>ROMANIAN DL: 2750 x3 x6, Barbell Hip Thrust: 950 x8 x8, Reverse DB Lunge: 350 x3 x8</td>
</tr>
<tr>
<td>12</td>
<td>BS: 3150 x6, 3250 x6, 3250 x6, Barbell Hip Thrust: 1450 x3 x8, SL Romanian DL: 40# x6, 500 x2 x8</td>
<td>BS: 3550 x6, 3650 x6, 3150 x6, Barbell Hip Thrust: 1550 x3 x8, 500 x2 x8, SL Romanian DL: 500 x2 x10, 500 x2 x10</td>
<td>BS: 3150 x6, 3650 x6, 3650 x5 x6, 3500 x5 x6, 3500 x5 x6, 3500 x5 x6</td>
</tr>
</tbody>
</table>
ABSTRACT

Background and purpose: Second anterior cruciate ligament (ACL) injury rates continue to be high, with a majority of injuries occurring soon after return-to-play, potentially because athletes may not be ready for the external load demands of the sport. Load metrics, tracked through wearable technology, may provide complementary information to standard limb symmetry indices in the return-to-play decision making process. The purpose of this case report was to quantify and monitor load using innovative technology during physical therapy rehabilitation after ACL reconstruction (ACLr) and compare to normative sport participation data.

Case Description: The subject was a 12-year-old female soccer player that suffered an ACL injury followed by surgical reconstruction with a hamstring autograft and standard rehabilitation. Single-leg hop performance, isokinetic strength, and external loads (using wearable technology) were measured longitudinally during rehabilitation and analyzed at the time of return-to-play.

Outcomes: The subject successfully achieved >90% LSI for isometric quadriceps strength (week 14), single leg hop battery (week 23), and isokinetic hamstrings (week 26) and quadriceps (week 31) strength by the time of return-to-play (week 39). At the time of return to play, external load metrics indicated that the subject's most intense rehabilitation session consisted of 36% less frequent movements, 38% lower total distances, and activity durations that were 29% lower than the expected demands of a match.

Discussion: Standard rehabilitation may underload patients relative to required sport demands. Measuring external load during the rehabilitation period may help clinicians adequately progress workload to the necessary demands of the patient's sport. With the current emphasis on restoring limb symmetry, clinicians may need to shift focus towards load preparation when returning a patient to their sport.

Level of Evidence: 4

Keywords: anterior cruciate ligament, load, rehabilitation, return to play, step count, movement system
BACKGROUND
Anterior cruciate ligament (ACL) injuries can be devastating because of the significant short- and long-term physical, psychological, and financial consequences.1,2 Most ACL ruptures are treated surgically, followed by long-term intense rehabilitation. Despite successful efforts to prevent these injuries,3 incidence rates remain high and continue to grow. In the United States, the rate of ACL reconstruction (ACLr) reached 73.6 reconstructions per 100,000 person years in 2014, up 22% over a 10-year span.4 ACL injuries are particularly high in multi-directional women’s sports like soccer, which has an incident rate of 2.0 injuries per 10,000 athletic exposures.5 These numbers indicate that the rehabilitation of individuals after ACLr will continue to be common practice in orthopaedic and sports physical therapy settings.

A majority of the population that suffer ACL injuries participate in sports and desire to return to their pre-injury sport. Rehabilitation can take 6-24 months before athletes are released back to participate in their sport. However, only 83% of athletes return to some level of sport after surgery,6 65% return to their pre-injury levels of activity, and 55% return to competitive sport.7 For those that do return to sport, the risk of a second ACL injury is high. Re-rupture of the surgical graft occurs 5.2% of the time,6 and up to 20% of individuals suffer a secondary tear of the contralateral ACL.8 Moreover, many of these secondary injuries occur shortly after return to sport, with 30% occurring within the first 20 athletic exposures and 52.2% occurring within the first 72 exposures.8 These data may indicate that current rehabilitation and return to play procedures are not optimally preparing athletes for return to play or identifying athletes incapable of a safe and successful return. Clinicians commonly use a testing battery that consists of self-report functional outcome measures (i.e. International Knee Documentation Committee Questionnaire [IKDC], the Knee Injury and Osteoarthritis Outcome Score [KOOS]), symmetry measures from single-leg hopping, and isokinetic strength tests. However, poor outcomes9-11 and second injury incidence in such close proximity to return to play8,12 indicates the need for continued efforts to optimize rehabilitation and return to sport practices.

Workload management is a hot topic in the field of sports medicine. External workload, or the mechanical work done by an athlete, is an often overlooked component of rehabilitation, despite evidence that links workload to injury risk.13 The 2016 consensus statement on return to sport from the First World Congress in Sports Physical Therapy emphasizes load management and progression as key components of return to sport practice.14 Current return to sport practices with individuals after ACLr encompass self-rated functional and neuromuscular performance symmetry tests, but do not account for the on-court or on-field demands associated with the sport to which an athlete is returning. Sports have varying demands of straight line running, jumping, directional changes, accelerations, and decelerations.15 Not having the requisite fitness to return to the full demands of the sport, or the inability to display biomechanical control throughout the duration of a practice or competition could conceivably factor into the high second ACL injury rate. Thus, the purpose of this case report was to quantify and monitor workload using innovative technology (e.g. wearable technology) during physical therapy rehabilitation after ACLr and compare to normative sport participation data. Data from this case report will attempt to shape future directions for incorporating load measures into rehabilitation and return to play clinical decision making.

CASE DESCRIPTION
History
The subject was a 12-year-old female club soccer player with no significant past medical history. On the day of injury, the subject was playing as an attacker in a competitive match. In the second half of the match, she was running (self-reported 60-70% speed) after a loose ball with two defenders in close pursuit. As the subject tried to split the defenders, she lunged for the ball and attempted to cut to the left and received a slight lateral perturbation to her trunk from an oncoming defender. The subject landed with a relatively straight knee that immediately buckled into a valgus position and caused the subject to fall. She experienced immediate pain, joint effusion, and muscle inhibition and was assisted off the field and subsequently sought medical care. An MRI completed two days after injury revealed a complete acute ACL tear, lateral femoral and posterior tibial condyle contusions, moderate joint effusion, and a low-grade sprain of the proximal posterior cruciate ligament.
The subject attended four sessions of pre-operative physical therapy over four weeks prior to surgery. These sessions focused on reducing joint effusion, regaining range of motion, promoting neuromuscular control of the quadriceps, hamstrings, gastrocnemius, and hip musculature, and patient education in a home exercise program.

**Surgical Intervention**

The subject's surgery consisted of arthroscopically assisted ACL reconstruction using a hamstrings autograft with suspensory fixation at the femur and tibia. The graft measured 9mm at the femoral attachment and 9.5mm at the tibial attachment.

**Examination**

The subject's initial post-operative physical therapy evaluation was performed four days after surgical intervention. The subject had been prescribed oxycodone as needed but ceased taking at five days post-op and subsequently managed pain with Tylenol and ice. All incisions were appropriately healing with no signs of infection. Physical examination findings were unremarkable and consistent with post-operative norms. Specifically, she presented with the following impairments: moderate pain (3/10), moderate joint effusion (2+ stroke test), and reduced knee range of motion (flexion= 80 degrees, extension= -3 degrees). Functionally, per the surgeon's protocol, the subject was limited to 50-75% weight bearing for two-weeks post-operatively with the use of bilateral axillary crutches. She wore a hinged knee brace (Telescoping TROM Advance Post-op Knee Brace, DJO Global, Inc, Dallas, TX, USA) that immobilized the knee at 0 degrees for the first two weeks after surgery. Instructions from the physician allowed the brace to be unlocked as tolerated at two-weeks post-op and progress from 50% to full weight bearing as tolerated. These impairments and limitations restricted her participation in age-appropriate social and sports activities. Her primary goal was to return to soccer at her full pre-injury level.

The subject and her family agreed to participate in a research study aimed at incorporating wearable technology into rehabilitation after ACLr. The lead physical therapist (JBT) informed her and her family that rehabilitation would follow standard physician-given and evidence based protocols as performed in conventional post-operative rehabilitation. The wearable technology would allow the clinical team to monitor her progress, but because of the lack of evidence regarding their use, would not drive clinical decision making in her case. The family provided written informed consent and the child provided written assent to participate in the study and allow the collected data to be submitted for publication. The study was approved by the High Point University Institutional Review Board prior to patient treatment.

**Rehabilitation**

Rehabilitation procedures (Table 1) and decision making were performed in the context of the physician-given post-operative protocol, guidelines

<table>
<thead>
<tr>
<th>Table 1. General overview of rehabilitation program emphasis by phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effusion Management</strong></td>
</tr>
<tr>
<td>Gait Normalization</td>
</tr>
<tr>
<td>ROM</td>
</tr>
<tr>
<td>Neuromuscular Control / Re-education</td>
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<tr>
<td>Strength</td>
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<tr>
<td>Proprioception</td>
</tr>
<tr>
<td>Endurance</td>
</tr>
<tr>
<td>Plyometric / Agility</td>
</tr>
<tr>
<td>Sport-Specific</td>
</tr>
</tbody>
</table>

XXX – emphasized
XX – performed, not emphasized
X – not emphasized, used when indicated
reported by the MOON group, and other current evidence. During the immediate post-operative phase (weeks 0-2), interventions were prescribed and performed to normalize gait, regain knee extension range of motion to neutral and knee flexion range of motion to 120 degrees, reduce effusion, care for surgical wounds, and introduce neuromuscular re-education of the lower extremity musculature (quadriceps focus). The early rehabilitation phase (post-operative weeks 2-6) focused on regaining full knee joint range of motion and progressing neuromuscular retraining to achieve functional strength and control in daily activities and a global rating of function ≥ 70%. The strengthening and control phase (post-operative weeks 7-15) emphasized maintaining full knee joint range of motion and introducing more moderate impact functional activities such as running, jumping and landing. During the advanced training phase (post-operative weeks 16-20), the focus of rehabilitation was running, jumping, and agility progressions. The final stage of rehab, the return-to-sport phase (post-operative weeks 21 to return to sport), continued to progress reactive, power, and sport-specific activities in the context of symmetrical lower extremity strength. The plan of care consisted of formal physical therapy 2x/week for 30 weeks, 1x/week thereafter until return to sport. The subject's treatment duration was not limited by any factor, with each session lasting for an average of 68 minutes. Overall, the subject completed 57 physical therapy rehabilitation sessions, equating to 1.7 visits per week. Because of the research focus of her patient care, the rehabilitation was not subject to reimbursement or treatment time constraints typical of traditional clinical settings.

OUTCOMES
The subject’s rehabilitation timeline milestones are reported in Table 2.

Traditional outcome measures
Self-perceived functional outcome measures. The subject completed a number of standard self-report functional psychological questionnaires every four weeks throughout her rehabilitation (Figure 2). Functionally, scores on the Knee Injury and Osteoarthritis (KOOS) Activities of Daily Living (KOOS-ADL) and KOOS-Sport scale reached greater than 90% at week 10 and 22, respectively. The Anterior Cruciate Ligament-Return to Sport after Injury (ACL-RSI) score, a measure of a patient’s perception of readiness to return to sport, showed dramatic increases after week 25 and was greater than 90% at week 39. Fear avoidance and kinesiophobia perceptions increased from surgery to week 10. As the subject grew more

<table>
<thead>
<tr>
<th>Measure</th>
<th>Goal</th>
<th>Week achieved (post-operative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait</td>
<td>Unassisted</td>
<td>Week 2.5</td>
</tr>
<tr>
<td>Controlled single-leg squat</td>
<td>&gt;70 degrees</td>
<td>Week 8</td>
</tr>
<tr>
<td>Double-leg jumping</td>
<td>Initiation</td>
<td>Week 12</td>
</tr>
<tr>
<td>Single-leg hopping</td>
<td>Initiation</td>
<td>Week 13.5</td>
</tr>
<tr>
<td>Isometric quadriceps strength</td>
<td>&gt;90% LSI</td>
<td>Week 14</td>
</tr>
<tr>
<td>Running</td>
<td>Initiation</td>
<td>Week 14.5</td>
</tr>
<tr>
<td>Hop battery</td>
<td>&gt;90% LSI</td>
<td>Week 23</td>
</tr>
<tr>
<td>Isokinetic hamstrings strength</td>
<td>&gt;90% LSI</td>
<td>Week 25</td>
</tr>
<tr>
<td>Isokinetic quadriceps strength</td>
<td>&gt;90% LSI</td>
<td>Week 31</td>
</tr>
<tr>
<td>Sport</td>
<td>Medical Clearance</td>
<td>Week 39</td>
</tr>
<tr>
<td>Sport</td>
<td>Unrestricted</td>
<td>Week 49</td>
</tr>
</tbody>
</table>

Figure 1. Top row shows MRI sagittal slices of the subject’s: a) ACL rupture and b) bone bruise pattern. Bottom row shows operative images of: a) ACL rupture and b) reconstructed ACL.
confident, both scores showed consistent reductions throughout the rest of rehabilitation, bottoming out at 9% for the Tampa Scale for Kinesiophobia-11 (TSK-11) and 0% for the Fear-Avoidance Belief Questionnaire (FABQ) at the time of return to sport.

**Hop battery.** Standard single-leg hop battery testing was initiated at week 22 when the physical therapist decided the subject could safely perform the procedures. Repeat testing was then performed every two to four weeks thereafter to monitor the subject's progress. The battery consisted of the single-leg hop for distance, timed single-leg 6m hop, single-leg triple hop for distance, and single-leg crossover hop for distance tests. Limb symmetry indices (LSI) were calculated by dividing the involved limbs data by the uninvolved limb. 90% LSI were achieved for all single-leg hopping tests by week 23.

**Movement quality.** Movement quality was assessed weekly using the drop vertical jump test (Figure 3). The subject stood atop a 31-cm with her feet shoulder width apart. She was instructed to drop off the box with both feet at the same time, land bilaterally and subsequently perform a vertical jump for maximal height. Quality was assessed qualitatively by observation in real-time with two-dimensional video. Specifically, components of the Landing Error Scoring System (LESS), such as landing symmetry, knee flexion, and frontal plane knee control were observed. The subject needed verbal cueing for knee flexion and minor cueing with a mirror for landing symmetry before consistently exhibiting proper biomechanics for the remainder of rehabilitation.

**Strength Testing.** Isometric strength testing of the quadriceps was initiated at week 8 in 90, 60 and 30 degrees of knee flexion using an isokinetic dynamometer (Humac NORM, CSMi, Stoughton, MA, USA). The subject's quadriceps strength progressed from ~55% LSI to >90% LSI at all angles by week 14. Because of the graft type, the subject performed conservative hamstring strengthening during this time and did not complete maximal isometric loading. Isokinetic strength testing at 60 and 180 degrees/sec was initiated for the quadriceps at week 16 and the hamstrings at week 24. The subject achieved >90% LSI for the quadriceps at week 31 and for the hamstrings at week 25.

**Figure 2.** Self-report a) functional and b) psychological questionnaires.

**Figure 3.** Landing biomechanics from a) drop land at 12 weeks (notice asymmetry in attempt to unload the left limb), and b) drop vertical jump at 37 weeks.
The subject wore the activity monitor during all waking hours outside of rehabilitation to quantify total daily loads (Figure 4a). On days of post-operative physical therapy, rehabilitation step count accounted for 26.5±8.9% of total daily steps (maximum = 45.2%).

Activity duration and distance rate. During rehabilitation, the subject also wore a tri-axial accelerometer around her waist (VERT, Mayfonk Athletic, Fort Lauderdale, FL, USA). Figure 4b shows the number of active minutes (number of minutes in which the accelerometer recorded an acceleration > 1G) during the most intense rehabilitation session of each post-operative week. Active minutes consistently increased from week 13 (12 mins) to week 21 (54 mins). Duration was relatively stable from week 20 to 37 (mean = 50.0 ± 6.4 minutes), before reaching the maximum of 65 minutes in week 38. Distance rates were calculated for weeks 20-38 by dividing the total estimated distance in a rehabilitation session by the active minutes (mean = 59.1 ± 11.2 m/min, max = 77.9 m/min).

Jump workload. The accelerometer also measured the frequency (count) and intensity (height) of each traditional workload measures
Session Rating of Perceived Exertion (sRPE). At the end of each rehabilitation session, the subject was asked to rate the intensity of the session as a sRPE. sRPE’s were fairly consistent over the first six weeks of rehabilitation at 3-4/10, increased to 6-7/10 between weeks 7-17, and finished at 7-8/10 for the final 22 weeks.

Novel Workload Measures
Steps and distance. To track the number of steps taken during rehabilitation sessions, a wearable activity tracker (Actigraph, Pensacola, FL, USA) was worn at waist level (weeks 7-39) throughout the duration of the rehabilitation session. Session step counts (Figure 4a) were highly variable and were dependent on the goal for the session and the time since surgery, with a maximum of 5,553 steps during the most intense rehab session in week 38. For the purpose of comparison to existing literature that has reported distance travelled in soccer matches, step count was converted to distance using her average step length (78.3 cm) during five self-paced walking trials, collected using standard 3D motion analysis techniques. Additionally
jump that exceeded the minimum threshold of 15.2 cm (6 inches) during the rehabilitation sessions. Figure 4c illustrates jump frequency for the most intense rehabilitation session of each post-operative week (weeks 13-39). As plyometric progressions were introduced, the jump frequency increased rapidly and peaked at week 23. At week 23, the physical therapist determined that the subject exhibited good movement quality and fitness with the plyometric progressions, thus reducing the volume of jumping and transitioning loads to more sport-specific explosive maneuvers like direction changes and cutting. Jump performance (Figure 4d) gradually increased from week 13 (maximum jump height = 29.2 cm) to a maximum in week 35 (66.3 cm). It is worth noting that maximum jump height was not the primary focus at each rehabilitation session.

**Relationship of workload measures to sport demands.** Normative values from a youth (U15) women's soccer match were extracted from a previous study and compared to the data collected during rehabilitation. Rehabilitation workload was considerably lower than the expected workload in a normal match. When compared to normative values of total distance travelled during a competitive soccer match (6961 m), the rehabilitation session with the largest estimated distance (4348 m) equated to only 62% of the workload that would be expected when fully immersed in return to play. In respect to activity duration, the average rehabilitation session was only 71.4% of the expected activity duration of a game (70 mins). Similar under-loading was seen in distance rate, as the average and maximum distance rate achieved during rehabilitation was 49% and 64% of average distance rates recorded in a match. Conversely, because of the progressive plyometric program incorporated into the advanced phases of rehabilitation, the subject significantly over-performed jump loads relative to game demand averages (1-4 jumps).

**Discharge/Return To Sport**
The subject was medically cleared (joint decision by physician and physical therapist) for restricted return to sport at post-operative week 37 after all standard tests were passed (Table 2) and the surgical graft had at least nine months to heal. The physical therapist was in constant contact with the subject's coach and family to ensure a progressive return to activity in training sessions and matches. The subject began with non-contact activities throughout practice and was slowly incorporated into contact drills within two weeks of return. After two weeks of full practice, the subject was cleared to return to game action for 10 minutes a half for the first month, increasing playing time by five minutes per half every 1-3 weeks until full safe participation was attained.

**DISCUSSION**
These data represent the progression of rehabilitation in an adolescent female subject after ACL reconstruction with an extremely successful short-term outcome. Results illustrate how to incorporate and quantify conventional physical performance, functional, and psychological measures with novel internal and external load measures during rehabilitation. Wearable technology is becoming more affordable, and in turn, accessible to clinical settings. While this type of technology does not currently allow for the collection of data as robust as what may be collected in a laboratory setting, it can provide clinicians unique internal and external load information that is not currently captured in conventional physical therapy settings. This case report may have immediate inexpensive translation to the clinical setting as some patients are fortunate enough to own their own wearable technology (i.e. Fitbit, iPhone) that can provide clinicians with reliable information (i.e. steps, distances) to help understand workload volume and tolerance to assist in clinical decision making, while other wearable technology can be purchased for nominal costs that are consistent with other physical therapy related equipment.

External workload data from this case report indicated significant under-loading of the subject during rehabilitation, despite successful outcomes. With ever-increasing demands on therapists' time and consistently decreasing reimbursement rates, a rehabilitation paradigm shift may be necessary. Late-stage rehabilitation in the return-to-sport phase may need to shift out of the clinic and towards the field, court, or athlete's training facility. The rehabilitation team, including the patient, physician, physical therapist, family, and coach, may need to collectively develop clear plans to re-integrate the patient from a relatively low load clinical setting to a high load training session. This subject received clinical care that did not have the typical constraints that
most clinics have. Fortunately, this case was part of a research study and did not require health insurance reimbursement to cover the cost of care. The physical therapist did not have a standard patient case load and was able to spend as much individualized time as needed with the subject and was able to give care in an 18,000 ft² facility that did not lack for clinical space. Therefore, the differences observed between rehabilitation load and expected game load during "gold standard" care are likely conservative estimates compared to traditional care settings. Results may suggest that other clinicians might also be severely under-loading athletes after ACL reconstruction during rehabilitation, despite thinking that their protocols and progressions significantly intensify over time.

In this case, clinicians did not use the workload data for clinical decision-making during rehabilitation progressions, but these data clearly indicate the need to incorporate workload measures in rehabilitation to ensure sufficient progressions and comparisons to benchmarks of patients' sports. For example, jump count and performance can be tracked in real-time. While most clinicians track plyometric progressions in terms of repetitions or sets, a total jump or impact count may provide richer data more analogous to pitch counts in upper extremity rehabilitation. While the system used to track steps taken did not provide real-time data, clinicians could easily obtain these results post-session. Progressions for impact counts, steps, or distances can also allow the clinician to track the acute:chronic workload ratio to ensure no sudden spikes in workload for which the patient has not yet developed the requisite fitness capacity to safely incur.

Workload measures may also prove beneficial in return-to-play decisions. Current standard physical tests look at limb symmetry indices during strength and performance tests, but do not account for the demands that an athlete will need to incur when they return to sport. In this case, rehabilitation helped the subject successfully pass the conventional testing battery in an appropriate amount of time and its hopeful that the subject will have excellent long-term outcomes. However, despite relatively consistent implementation of these tests in clinical settings, the incidence of second ACL injury is around 25%, with 30% of second injuries occurring in the first 20 exposures after return to play. These athletes may have exhibited symmetrical strength and power, adequate movement quality, and good perceived function, but may not have adapted to the levels needed in their sport. Previous studies have linked large spikes in workload (particularly total distance) to lower extremity injury, which could be representative of an athlete that returned to sport after relatively low loading in physical therapy. Clinicians could consider incorporating simulated games as part of the in clinic or home exercise program and monitor load both in and out of rehabilitation.

A major limitation to incorporating workload monitoring into rehabilitation is the amount of time and space needed. In this case example, 70 minutes of activity and approximately 7000 m of distance would be recommended to simulate the demands of the subject's sport. While having the subject obtain these loads unsupervised on a treadmill might meet the target, this single type of loading does not incorporate the multi-directional demands of the sport and does not allow the clinician to provide adequate feedback or movement quality that has been shown to predict second ACL injury. Future work is needed to monitor workload during rehabilitation in a cohort of patients with various clinicians and settings to verify the findings from this case report and validate these measures as a potential risk factor for second injury.

CONCLUSIONS
The results of this case report suggest that standard rehabilitation, though effective at achieving limb symmetry goals, may underload patients relative to their required sport demands. Measuring external load during the rehabilitation period may help clinicians adequately progress workload to the necessary demands of the patient's sport. With current clinical emphasis on restoring limb symmetry, clinicians may need to shift focus towards load preparation when returning a patient to their sport.

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2. Lie MM, Risberg MA, Storheim K, et al. What's the rate of knee osteoarthritis 10 years after anterior cruciate...


ABSTRACT

**Background and Purpose:** Postural Restoration Institute® (PRI) theories and rehabilitation techniques focus on restoring balance to anatomical systems. Common postural asymmetries can present in athletes as dysfunctions and limitations. The purpose of this case report was to examine the use of PRI exercises and theories to address pelvic alignment, along with core stabilization, during treatment of shoulder dysfunction in a collegiate volleyball player.

**Case Description:** A 22-year-old female volleyball athlete reported unresolved right rotator cuff tendinopathy. She presented with bilateral rib cage flare, anterior pelvic tilt, and bilateral ROM differences in hip and shoulder internal and external rotation. PRI® special test findings included a positive left and right Adduction Drop Test (ADT), positive left Extension Drop, and Hruska Adduction Lift test (left=2, right=3) indicating posterior exterior chain (PEC) pattern of dysfunction. The traditional shoulder rehabilitation program from the previous season was eliminated and a PRI based intervention was performed. Intervention exercises included the 90/90 dead bug diaphragmatic breathing, 90/90 hamstring hip lift, and right sidelying respiratory left adductor pull back. Exercises were performed as three sets of ten diaphragmatic breathing repetitions, a minimum of three times weekly prior to activity.

**Outcomes:** Likert scale ratings of pain decreased from a six pre-intervention to two. The left hip gained 10° of internal rotation and the right hip gained 14° of external rotation. Right shoulder internal rotation increased 15°. Hruska Adduction Lift improved to a four bilaterally (right by day 24, and left by day 31). Left extension drop test was negative following day 17.

**Discussion:** PRI® exercises focusing on core and pelvic stability translated to improved hip and shoulder ROM, and decreased shoulder pain associated with rotator cuff tendinopathy. By treating pelvic alignment with the PRI® exercises, the ROM imbalance and pain at the shoulder joint were addressed.

**Conclusion:** Incorporating PRI exercises and theories into the rehabilitation program of a volleyball player was useful in addressing underlying imbalances throughout the kinetic chain.

**Level of Evidence:** 3b

**Keywords:** Breathing exercises, Postural Restoration, rotator cuff pathology, shoulder, volleyball
**BACKGROUND AND PURPOSE**

Many overhead athletes experience generalized shoulder pain due to repetitive terminal external rotation, with abduction and elevation. Common, and often successful, rehabilitation programs for shoulder pain focus on strengthening, mobility, and sport specific movements targeting the involved joint. However, some athletes continue to report unresolved chronic shoulder injuries, indicating potential underlying dysfunction away from the primary anatomical site of pain generation. These underlying pathologies could provide necessitate use of an alternative treatment approach for those athletes who are unresponsive to traditional treatment methods.

Treatment paradigms by Ron Hruska at Postural Restoration Institute® (PRI) integrate posture-based intervention programs for the management of musculoskeletal injuries and asymmetries assumed to be present due to postural adaptations. PRI theorizes that common postural asymmetries can present in athletes as dysfunctions and movement limitations and incorporates multiple systems (musculoskeletal, nervous, and respiratory) to influence movement patterns. Postural restoration treatment (PR) aims to restore balance and variability to these anatomical systems. Once these dysfunctional adaptations are corrected, patients can perform activities with greater efficiency, even without direct intervention to the affected joint or region. In theory, if these postural adaptations are corrected, then dysfunction is decreased throughout other systems in the body. Despite the increased use of PRI theories by sports medicine clinicians, there is limited, but promising, published evidence on PR treatment outcomes. The purpose of the current case report is to evaluate the use of a PR treatment intervention to address chronic shoulder pathology that failed to be alleviated using traditional intervention methods.

**CASE DESCRIPTION**

A 22-year-old, female, Division I volleyball player, with 14 years of competitive experience, was seen for generalized right shoulder pain mid-way through the fall competitive season (in-season). She sought treatment due to her rehabilitation plan from the previous volleyball season no longer effectively treating her chief complaints of right shoulder pain and rotator cuff weakness/fatigue. She was diagnosed during the previous competitive season (season one) with right rotator cuff tendinitis. Previous medical history revealed no prior orthopedic surgery, but the athlete reported hip dysplasia that required her to be in a Pavlik harness for two months after birth by cesarean section due to breech positioning. No other previous orthopedic issues were documented prior to the shoulder pain. She was treated throughout season one with a traditional rotator cuff tendinitis rehabilitation plan, which included strengthening, mobility, and range-of-motion (ROM) exercises. She was given a list of thirteen exercises and completed the program by choosing any four exercises at 3 sets of 10 repetitions, four times a week (Table 1). She was instructed to cycle through the exercise options and not repeat the same exercise in consecutive days. Modalities supplemented the program for pain modulation including interferential stimulation, thermal therapy, and cryotherapy. The athlete reported continued use of the rehabilitation plan.

The athlete’s playing time increased from the season one to season two, the competitive season in which the case report took place. Despite being a middle blocker, she had multiple games during season two where she played the full rotation and served for herself throughout the whole year. Differences in game activity between seasons are presented in Table 2. Strength and conditioning session participation was team based in both years and remained relatively

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**Table 1. Traditional Treatment Plan and Volleyball Warm-Up**

<table>
<thead>
<tr>
<th>Traditional Rehabilitation Exercises to Address Rotator Cuff Tendinitis*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder flexion, extension, abduction &amp; adduction with elastic resistance band</td>
</tr>
<tr>
<td>Dumbbell shoulder press</td>
</tr>
<tr>
<td>Shoulder front raises</td>
</tr>
<tr>
<td>Standing, bilateral Ys, T’s, T’s with 3-5 pound dumbbells</td>
</tr>
<tr>
<td>Seated dumbbell shoulder external rotation</td>
</tr>
<tr>
<td>Dumbbell proprioceptive neuromuscular facilitation D1 &amp; D2 patterns</td>
</tr>
<tr>
<td>Body Blade through proprioceptive neuromuscular facilitation patterns</td>
</tr>
<tr>
<td>Body Blade shoulder flexion</td>
</tr>
<tr>
<td>Rows with elastic resistance band</td>
</tr>
<tr>
<td>Latissimus dorsi pull down with elastic resistance band</td>
</tr>
<tr>
<td>Dumbbell weighted shoulder flexion with manual perturbations</td>
</tr>
</tbody>
</table>

**Table 2. Volleyball Warm-Up Exercises with Elastic Resistance Band**

<table>
<thead>
<tr>
<th>Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapular rows</td>
</tr>
<tr>
<td>Combination movement of right row followed by shoulder E/R to 90°</td>
</tr>
<tr>
<td>Thumb down (empty can) shoulder V raises</td>
</tr>
<tr>
<td>Shoulder internal rotation, elbow at side</td>
</tr>
<tr>
<td>Shoulder external rotation, elbow at side</td>
</tr>
<tr>
<td>Simulated arm swings each side</td>
</tr>
</tbody>
</table>

*Performed during season one, †Performed during season two
consistent with the previous year’s volume. She was seeking new treatment options mid-season two, as she felt her shoulder pain was hindering her performance. Her treatment goal was to play pain-free.

CLINICAL IMPRESSION #1
The subject’s chief complaint of chronic shoulder pain, despite continued rehabilitation for over one year, indicated that the rotator cuff tendinitis was likely not resolved. Furthermore, it was believed that underlying pathologies needed to be explored.

EXAMINATION
During the season two examination to globally evaluate the shoulder girdle, the subject presented with bilateral rib cage flare and anterior pelvic tilt during standing shoulder flexion in the scapular plane. Range of motion (ROM) evaluation revealed hip and shoulder internal and external rotation asymmetries (Table 3). Manual muscle testing performed on the shoulder revealed the subject’s strength was 5/5, bilaterally, in all planes of motion. The subject had positive test results for Hawkins-Kennedy and Neer Impingement special tests on the involved shoulder; all other orthopedic special tests were unremarkable. PRI® recommended special tests performed by the PRI trained clinician included: Adduction Drop Test (ADT), Extension Drop Test (EDT), and Hruska Adduction Lift Test (HAdLT).

The ADT (Figure 1) and EDT (Figure 2) were performed as described by Masek. The ADT has the subject placed in a side-lying position with the both legs positioned in 90° of hip and knee flexion (Figure 1). The clinician stands behind the subject to passively flex, abduct, and extend the hip, while the knee remains in 90° of flexion. The hand of the clinician

Table 2. Volleyball Performance Statistics for Subject

<table>
<thead>
<tr>
<th></th>
<th>Season One</th>
<th>Season Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volleyball Match Sets Played</td>
<td>121</td>
<td>130</td>
</tr>
<tr>
<td>Assists Per Set</td>
<td>0.07</td>
<td>0.22</td>
</tr>
<tr>
<td>Total Digs</td>
<td>74</td>
<td>160</td>
</tr>
<tr>
<td>Digs Per Set</td>
<td>0.61</td>
<td>1.23</td>
</tr>
<tr>
<td>Serve Receptions</td>
<td>3</td>
<td>207</td>
</tr>
<tr>
<td>Aces Per Set</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>Blocks Per Set</td>
<td>1.07</td>
<td>1.00</td>
</tr>
<tr>
<td>Total Attacks</td>
<td>723</td>
<td>667</td>
</tr>
<tr>
<td>Kills Per Set</td>
<td>2.21</td>
<td>1.90</td>
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</table>

Table 3. Active Range of Motion Measures

<table>
<thead>
<tr>
<th></th>
<th>Pre-Intervention</th>
<th>Treatment Day 10</th>
<th>Treatment Day 17</th>
<th>Treatment Day 24</th>
<th>Treatment Day 31</th>
<th>Treatment Day 38</th>
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<tbody>
<tr>
<td><strong>Hip Range of Motion</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>100°</td>
<td>110°</td>
<td>104°</td>
<td>110°</td>
<td>106°</td>
<td>111°</td>
</tr>
<tr>
<td>Extension</td>
<td>10°</td>
<td>6°</td>
<td>10°</td>
<td>8°</td>
<td>12°</td>
<td>11°</td>
</tr>
<tr>
<td>Adduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abduction</td>
<td>18°</td>
<td>20°</td>
<td>10°</td>
<td>8°</td>
<td>12°</td>
<td>11°</td>
</tr>
<tr>
<td>Abduction</td>
<td>34°</td>
<td>29°</td>
<td>37°</td>
<td>30°</td>
<td>42°</td>
<td>36°</td>
</tr>
<tr>
<td>Internal Rotation</td>
<td>23°</td>
<td>38°</td>
<td>26°</td>
<td>36°</td>
<td>27°</td>
<td>35°</td>
</tr>
<tr>
<td>External Rotation</td>
<td>35°</td>
<td>20°</td>
<td>35°</td>
<td>22°</td>
<td>36°</td>
<td>25°</td>
</tr>
<tr>
<td><strong>Shoulder Range of Motion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal Rotation</td>
<td>50°</td>
<td>47°</td>
<td>52°</td>
<td>50°</td>
<td>44°</td>
<td>52°</td>
</tr>
<tr>
<td>External Rotation</td>
<td>84°</td>
<td>95°</td>
<td>85°</td>
<td>95°</td>
<td>86°</td>
<td>96°</td>
</tr>
</tbody>
</table>

*The right shoulder was the involved, painful limb
not completing passive ROM maintains the position of the top innominate. A positive test is indicated when the knee of the upper leg is unable to contact the table when the knee is release and hip position is maintained; this finding indicates a restriction of the piri-formis muscle or transverse ligament, or impact of the posterior inferior femoral neck on the posterior interior rim of the acetabulum blocking adduction. The subject was found to have a positive left and right ADT.

The EDT has the subject positioned on the end of the table with both knees to the chest, mirroring the setup of Thomas test (Figure 2). The tested leg is passively lowered by the clinician while holding the subject's untested leg close enough to the chest to maintain contact of low back with the table. The clinician then lowers the testing limb downward, ensuring that the hip does not abduct, which results in a false negative position. A positive test is present when the testing leg thigh is unable to touch the table, indicative of a restriction in hip extension. The subject demonstrated a positive left EDT.

The HAdLT (Figure 3) is performed with the subject positioned in sidelying with the back slightly rounded forward. The ankle of the upper leg rests on the clinician's shoulder, which indicates the side being tested. For example, if the subject is lying on his/her right side with his/her left leg on the clinician's shoulder it would be considered a Left HAdLT. In this position the hip should be in a neutral alignment and the knee fully extended. This test is graded by the clinician's evaluation of the movements accomplished successfully. The progression of movement is as follows: 1) the subject was asked to raise the ankle of the flexed lower leg to knee of the leg resting on the shoulder of the clinician, 2) the knee of the lower leg is raised off the table while the ankle maintains contact with the knee, and 3) the subject was asked to raise the lower hip of the table while maintaining the first two positions. If at any time during this movement the athlete was unable to accomplish or hold the previous position the test was stopped.

The HAdLT test is graded on a zero to five scale and the ability to accomplish the movements is the criteria for grading. For a zero grade the subject is unable to raise the lower leg to the knee presenting as obturator weakness. Grade one occurs when the subject can raise the ankle, but is unable to raise the knee. This reflects weakness in the external rotator muscles of femoral acetabular (FA) joint more commonly, or weakness of the active extremity stabilizing muscles of the acetabular femoral (AF) joint. The FA and AF joint are the same joint, distinguished by the leading listed bone moving on the second listed bone. Grade two is the ability to raise the lower knee while maintaining ankle positioning. The current subject received a two grade on her left side, indicating instability of the AF joint and weakness of adductor magnus, and obturators; or there being a forward rotated pelvis with FA joint internal weakness. Grade three rating indicates the subject is able to hold Grade two while slightly raising his/her hip off the table. The current subject received a grade three on her right side. Inability to do this reflects weakness of the FA joint stabilizers on the extended leg, and the possibility of bilateral AF joint stabilizers weakness. Grade four rating is the subject's ability to raise the hip off the table to the level of his/her shoulder and the clinician's shoulder. The inability to accomplish this task reflects a weakness in lumbopelvic strength and a general weakness of the obliques bilaterally. Grade five rating is the ability to raise his/her hip above the clinician's shoulder and his/her own shoulder. The inability to accomplish this task reflects the lack of strength and proprioceptive ability to shift his/her hips.

Clinical Impression #2

Evaluation findings, particularly the positive ADT bilaterally, indicated a Posterior Exterior Chain (PEC) pattern. The PEC pattern, unlike many of the movement patterns defined by PRI®, is a bilateral pelvic alignment compensation. In this pattern, both ilia
are anteriorly tilted increasing lordotic curvature in the lower back. This pelvic tilt is commonly associated with a bilateral rib cage flare; which in turn creates an inability to expand the lower portion of ribs to full capacity while taking a deep breath, as well as abdominal oblique disuse. Successful PR-based intervention would reduce asymmetries in hip and shoulder internal and external rotation ROM, and result in negative PRI special test findings.

**INTERVENTION**

The timeline reported in this case study began midway in season two with pre-intervention measurements and initial implementation of the program. The final follow-up measurements were performed 38 days later. At that time the athlete was unable to complete the intervention program three times during the remaining two weeks of regular season because of a partial Achilles tendon rupture shifting the focus of care. While she continued to play the remainder of the season, ankle pain management and strengthening was priority became the priority of rehabilitation.

The athlete’s former traditional shoulder rehabilitation program was eliminated at the onset of PR treatment program. A heat pack on the right shoulder was used by the athlete prior to competition and practices as part of her own warm-up routine. Additionally, the athlete completed a traditional, team-based volleyball bilateral shoulder warm-up routine at one set of fifteen repetitions prior to practice and competition (Table 1).

Information gained from the pre-intervention assessments of the athlete allowed for a development and implementation of a PR intervention program (Table 3). This included one adapted intervention using PRI theories and two specifically recommended interventions by PRI. The interventions included an adapted 90/90 dead bug diaphragmatic breathing, 90/90 hip shift with hemi-bridge, and right side-lying respiratory left adductor pull back (Figure 4). The exercise order was chosen to address the sagittal plane compensations, followed by frontal plane compensations. Each intervention exercise was performed in three sets of ten repetitions of diaphragmatic breathing. The subject was instructed and given direct feedback for an initial two-week period. Feedback consisted of tactile and verbal cues while completing the intervention program. Cues correcting her positioning and breathing patterns were used to ensure proper form and muscle activation was achieved. After two weeks, she was allowed to perform the intervention program without direct supervision, while still reporting completion. The intervention program was completed three times a week prior to activity, at minimum, with a full reassessment at the start of each week.

**PR Treatment Intervention Exercises**

For the 90/90 dead bug position, the athlete positioned herself into 90° of hip flexion, 90° of knee flexion, feet shoulder width apart, 90° of shoulder flexion, and a rolled towel under her neck to open the airway (Figure 4A). The athlete was instructed to inhale as much air in as she could using her abdominal and diaphragm musculature. She was told to pull the air down into her belly and torso achieving maximum lung volume every inhalation. This allowed her diaphragm to create a negative pressure in the thorax cavity and force air into the lungs. When she exhaled through her mouth, she was cued to imagine she was blowing a balloon up. As she exhaled, the lower portion of the rib cage would position itself down and rotated toward midline. This breathing pattern helps engage the core musculature and the diaphragm to expand the lungs to achieve maximum volume with each breath. PRI recommends the physical use of a balloon to engage
core musculature throughout the breathing pattern. However, this exercise was adapted to visualizing a balloon due to inaccessibility. The PRI® recommended 90/90 hip shift with hemi-bridge was completed as described previously, with minor modifications (Figure 4B). The modifications included a rolled towel placed underneath her neck and a foam roller. For this exercise the clinician must ensure the bolster between the feet causes the left knee to fall below the left hip. This exercise’s main goal is to shift the femoral head more congruently into the socket of the acetabulum. This is done by activating and cueing the subject to first pull their left femur back towards their left ilium. Once this is done, he/she is instructed to hold that position and drive their left knee down into the towel placed between the knees. This pull back and downward drive of the left knee will activate the left adductor, gluteus medius, semimembranosus, and semitendinosus muscles.

Outcome Measures
Measures to evaluate overall progress of the intervention program included both subject and clinician reported outcome measures. A 10-point Likert-pain scale rating was used as a patient reported outcome. This rating was reported verbally by the athlete after each completion of the intervention program. Clinician reported outcome measures comprised of PRI recommended special tests, including the ADT, EDT, and HAdL, and hip and shoulder active ROM.

The ADT was completed bilaterally after each completion of the intervention program. This ensured that proper pelvic neutrality was achieved by the athlete. This special test was chosen because of the direct feedback obtained by the clinician about the exercises’ effect on pelvic alignment.

The shoulder ROM measurements were taken bilaterally and included flexion, extension, internal rotation, external rotation, abduction. Hip included the same ROM listed for shoulder along with adduction. All ROM measurements were taken by the same clinician as described in Starkey et al., with the exception of shoulder extension. Shoulder extension was modified and measured from a standing position with her elbow flexed to 90° then actively moved posteriorly into extension.

OUTCOME
The verbal, Likert pain scale rating for the subject showed an overall decrease from pre-intervention (6/10). Pain was reported to be a 2/10 or lower from day 11 of the intervention to the end of the evaluation period. The athlete's ROM improved throughout the intervention program as seen in Table 3. Shoulder forward flexion and abduction were not included in this table as the athlete had 0-180° of ROM, bilaterally, throughout the course of intervention. Her right shoulder gained 15° of internal rotation. The athlete's left hip gained 10° of internal rotation, while her right hip gained 14° of external rotation.

PRI® recommended special tests indicate improvement throughout the intervention program. ADT was negative following each treatment session, indicating treatment success. The right EDT was negative for the athlete pre-intervention and did not change. The left EDT was positive pre-intervention, and improved to negative following intervention day 17. The Right HAdLT improved to a four on intervention day 31, while the Left HAdLT improved to a four on intervention day 24.

During the exit physical upon the completion of the athlete's collegiate playing career, an MRI was performed on her right shoulder. Diagnostic imaging
indicated minor blunting and fraying of the posteroinferior labrum, and mild diffuse tendinosis along the rotator crescent. These findings are consistent with the subject's chronic tendinopathy and confirmed no major underlying pathological damage as the cause of the right shoulder pain.

DISCUSSION
The presentation of the PEC pattern in this athlete was typical, as described by PRI®. PEC is theorized to cause the right and left hip to position in external rotation, abduction, and flexion resulting in bilateral rib cage flare and anterior pelvic tilt. Current literature has shown that lumbopelvic and core weakness/instability negatively affects the upper extremity in patients, resulting in dysfunction. The PEC pattern present in this athlete reflected lumbopelvic and core weakness/instability. This information gained from the assessment led to the clinical reasoning that underlying lumbopelvic and core weakness/instability was contributing to the athlete's shoulder dysfunction. Thus, by using PR treatment to address the lumbopelvic and core weakness/instability the subject's shoulder pain could potentially be addressed.

Structuring the athlete's intervention to target the pelvis's dysfunctional patterns was the main focus of the program. The adapted 90/90 dead bug diaphragmatic breathing was used to activate the core muscles, postural stabilization muscles, address the sagittal plane needs and prime the breathing pattern of the athlete for the remainder of the intervention program. During activity the body has increased respiratory demands to meet the basic needs of the athlete. This respiration increases activation of postural stabilization muscles. The 90/90 dead bug was always completed first, to cue the athlete to focus on core activation and the diagrammatic breathing pattern throughout her therapeutic exercises.

The 90/90 hip shift with hemi-bridge targeted the anterior pelvic tilt and activation of the adductor muscle group. This athlete’s ADT showed a bilateral anterior tilted pelvis. The 90/90 hip shift was used to target unilateral hamstring activation. The ipsilateral activation of the hamstring pulls on the ischial tuberosity creating a posterior translation of the pelvis. This unilateral activation decreases lumbar lordosis and increases anterior rib depression. Once the pelvis is in a more neutral position the femoral head should adduct more freely because it will not come in contact with the cotyloid rim of the acetabulum. The right sidelying left adductor pull back targeted the external rotation of the pelvis and congruence of femoral head into the acetabulum. This intervention promotes hip adduction and left femoral internal rotation on acetabulum. During the inhalation process the diaphragm forces the pelvic floor to open the AF joint specifically, easily allowing internal rotation, decreasing limitation of movement, and addressing the frontal plane compensations.

The PRI based intervention program’s significant effect on symptom resolution could be attributed to the ROM gained at both the hip and shoulder. Rates of shoulder injuries in baseball pitchers are inversely correlated to hip rotational ROM and decreased hip rotation ROM has been correlated to increased shoulder external rotational torque. The athlete in this case study drastically improved her left hip internal rotation ROM over the course of the PRI intervention. In theory, this hip ROM improvement may have decreased the torque on her shoulder, and thus decreased right shoulder joint musculature demands.

A possible confounding factor noted in this case was the athlete's hip dysplasia at birth. Having minor dysplasia that goes undetected or is improperly treated in infant and adolescent years can lead to greater morbidities later in life. These morbidities result from abnormal hip biomechanics leading to more anatomical abnormalities because of the improper movement patterns. Whether the athlete's hip dysplasia was truly corrected as an infant, and if the irregular movements developed subsequently due to her sport or movements being expressed as dysfunctional postural patterns are related to this previous medical history is unknown.

There are some potential limitations to the current case report. In this specific case report, outcome measures to assess shoulder strength, beyond manual muscle testing, or fatigue of the athlete were not evaluated. The use of hand-held dynamometry would have enhanced the assessment of strength. The athlete did subjectively report that throughout her intervention shoulder fatigue decreased as she progressed further into the program. This information though not
assessed shows an area for future studies to assess the effects of postural restoration interventions on shoulder fatigue and strength. The current case used a single-item patient-reported outcome (Likert scale) to evaluate pain. However, a validated multi-item scale, such as the Disabilities of the Arm, Shoulder and Hand (DASH), would have provided a more complete view of the subject's pain and function. Lastly, well-designed research evaluating the PRI interventions are necessary, as case reports are limited in their generalizability and assessment of causal relationships.

**CONCLUSION**

The results of this case report suggest that PRI® exercises focusing on core and pelvic stability can translate to improved ROM and decreased shoulder pain associated with rotator cuff tendinopathy, even when traditional interventions are removed. PR-based interventions address postural asymmetries in the kinetic chain that present as movement dysfunction. By treating pelvic alignment with the PRI® exercises and theories, shoulder pain and ROM measures in this overhead athlete were improved.

**REFERENCES**


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