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ABSTRACT

Background: While static stretch (SS), proprioceptive neuromuscular facilitation (PNF) and oscillatory physiological mobilization techniques are documented to have positive effects on a range of motion (ROM), there are no reports on the effect of dynamic oscillatory stretching (DOS), a technique that combines these three techniques, on hamstring extensibility.

Purpose: To determine whether DOS improves hamstring extensibility and stretch tolerance to a greater degree than SS in asymptomatic young participants.

Study Design: Randomized Controlled Trial.

Methods: Sixty participants (47 females, 13 males, mean age 22 ± 1 years, height 166 ± 6 centimeters, body mass 67.6 ± 9.7 kg) completed a passive straight leg (SLR) to establish hamstring extensibility and stretch tolerance as perceived by participants, using a visual analogue scale (VAS). Participants were randomly assigned to one of two treatment groups (SS or DOS) or a placebo control (20 per group). Tests were repeated immediately following and one hour after each intervention. Data were assessed using a two-way repeated measure analysis of variance (ANOVA) and Tukey’s post hoc test.

Results: Immediately post-intervention, there was a significant improvement in the hamstring extensibility as measured by the SLR in both the SS and DOS groups, with the DOS group exhibiting a significantly greater increase than the SS group (Control 73 ± 12°, SS 86 ± 8°, DOS 94 ± 11°, p < 0.001). One hour post-intervention, hamstring extensibility in the DOS group remained elevated, while the SS group no longer differed from the control group (Control 73 ± 12°, SS 80 ± 8°, DOS 89 ± 12°, p = 0.001). Furthermore, the stretch tolerance remained significantly elevated for the SS group, but there was no difference between the control and DOS groups, (Control 4.6 ± 1.3, SS 5.9 ± 0.8, DOS 4.3 ± 1.0 AU, p < 0.001).

Conclusion: DOS was more effective than SS at achieving an immediate increase in hamstring extensibility, and DOS demonstrated an increased stretch tolerance one-hour post-intervention.

Level of evidence: 2C

Keywords: Dynamic oscillatory stretching, hamstring extensibility, stretch tolerance.

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INTRODUCTION

Reduction in the extensibility of the hamstring muscles has been reported to be associated with the occurrence of back pain,¹ sacroiliac joint disorders,² hamstring strain,³ patellofemoral pain syndrome,⁴ and patellar tendinopathy.⁵ Thus, extensibility of the hamstrings is important for optimal joint and muscle function. The extent to which muscles contract has been shown to be dependent on muscle length, and shortened or lengthened muscles may not develop maximum tension if their resting length has changed.⁶ The physiological mechanisms behind the changes in muscle extensibility are debatable. Viscoelastic, reflex muscle relaxation, and stretch tolerance changes⁷ have been extensively studied and are widely regarded as contributing to short- and medium-term alterations in muscle extensibility. More recently, there has been increasing attention being paid to Neurodynamics.⁸ Of these four mechanisms, the scientific literature mostly cites stretch tolerance for producing short- and medium-term alterations.⁷,⁹,¹⁰ Increased stretch tolerance means that stretching intervention enables individuals to tolerate higher levels of stretch discomfort rather than reflecting an actual change in the passive mechanical properties of tissue. In a well-designed study involving 60 healthy individuals, Ben and Harvey⁹ showed that static stretching did not induce any lasting changes in muscle extensibility. Rather, it merely improved participants’ tolerance for the discomfort associated with stretch, although it was not possible to ascertain the underlying physiological mechanism responsible for the improved stretch tolerance. The authors postulated that stretching has an influence on some characteristics of the sensory neural pathways stimulating muscle and joint mechanoreceptors, and this may reduce the sensation of pain.⁹

Static stretch (SS) is commonly utilized to increase range of motion (ROM), to improve performance, to prevent or reduce injury risk, and to reduce delayed onset muscle soreness.¹¹ However, research consistently shows that apart from improving extensibility, SS is largely ineffective in achieving the above-mentioned outcomes.¹¹,¹² The current study introduces a novel stretching technique – dynamic oscillatory stretching (DOS). DOS is a modified proprioceptive neuromuscular facilitation (PNF) technique. DOS is similar to agonist contract-relax (ACR),⁷ in that the agonist produces the stretching force on the opposite muscle (antagonist.) In this study the quadriceps femoris muscle, when attempting to stretch the hamstrings, is contracted to actively move the lower extremity into increased ROM utilizing the reciprocal inhibition mechanism.⁷,¹¹ In addition, DOS incorporates as a modification a two-second oscillatory manual stretch at the end of the range, which is applied by the therapist to assist the agonist.¹⁵ DOS therefore consists of dynamic, oscillatory and passive stretching components. In several studies, dynamic stretches, including ACR, have been shown to be superior to SS in achieving greater ROM as well as improving the function of the antagonist muscles.⁷,¹⁴ The oscillatory component of DOS resembles oscillatory physiological mobilization as described by an Maitland,¹⁶ for the treatment of musculoskeletal disorders. Mobilization techniques have consistently been shown to be clinically effective in improving peripheral and spinal joint mobility.¹⁷,¹⁸ It is therefore postulated that DOS is a potentially superior technique to SS in improving ROM as it incorporates three evidence-based modalities (PNF, oscillatory passive physiological mobilization and SS), all of which have been clinically proven to increase ROM.¹¹,¹³,¹⁴

To date, no reports have been found in the literature describing the effectiveness of DOS on hamstring extensibility and stretch tolerance. The purpose of this study was to compare the effects of static and dynamic oscillatory hamstring stretching on SLR, which is a measurement of hamstring extensibility. The study also used a visual analog scale to measure the most intense perception of pain as a proxy measurement at the point of greatest stretch tolerance, immediately and one hour after the performance of SS and DOS techniques in asymptomatic young adults.

The research hypotheses were that hamstring extensibility would be affected more by DOS than SS, and that DOS would affect the self-reported perception of pain at the limit of the SLR.

METHOD

Design

The study was a randomized controlled trial with blinded outcome assessment. Treatment could not
be blinded to the investigator or the subjects. Random number sequencing was generated using the Research Randomizer Computer Program by an independent investigator on the research team. The numbers were placed into individually sealed opaque envelopes, which were handed to participants after they had each undergone their baseline assessment. Participants were then randomly assigned to one of three treatment groups: SS, DOS, or control. The dependent variables were the degree of SLR ROM, and the subjects’ perceived pain. The independent variables were time (pre-, immediately post, and one-hour post); and the three types of intervention: SS, DOS, and control. Sample size estimation was performed a priori, and determined that a sample size of nineteen participants per group would detect a clinically important difference of 5° in SLR ROM with the power of 90% and $\alpha = 0.05$.

**Participants**
Sixty-nine healthy young physiotherapy students recruited from a local university volunteered to participate in the study. Participants were excluded if they had a previous history of lower-extremity and/or back pathology, and/or direct injury to the hamstring muscles in the previous six months; if they suffered from a neurological disorder; if they participated in a regular stretching regimen of the hamstring muscles group; or if they attended regular yoga classes. Volunteers were eligible for the study if their hamstring extensibility, as measured by SLR ROM, was less than or equal to 90° of hip flexion. In accordance with other studies which excluded participants with flexibility greater than 90°, nine participants with hamstring extensibility greater than 90° were excluded from this study, leaving 60 participants (47 females and 13 male) (Figure 1).

**Outcome measures**

*Primary outcome:* Measurements of hamstring extensibility performed with hip flexion and the knee in extension is referred to as the passive SLR test, which also reflects tension of the hip joint capsule and/or neural tissues. The SLR test demonstrates accepted inter-observer reliability (ICC 0.93 to 0.97). The measurements of SLR were performed by a research assistant, an experienced physical therapist, who was not present during the stretching treatment of each participant. Her within-session intra-rater reliability was previously determined as ICC = 0.89, with the Standard Error of Measurement < 1°.

The SLR measurement position was the same as the starting position of each stretching protocol. A hand-held inclinometer that measures in two degree increments (Isomed, US Neurologicals LLC, Washington, USA) was used to measure SLR ROM. The proximal peg of the inclinometer was placed on the tibial tuberosity with the second peg parallel to the shaft of the tibia (Figure 2). The reliability of this measurement tool for SLR is ICC = 0.95 to 0.98. The authors adapted the Maitland-style movement

![Flow diagram for recruitment, follow-up and analysis](image-url)
The main investigator (first author) who performed the intervention on each participant and was not involved in the measurements has 30 years of experience in physical and manual therapy according to the Maitland concept.\textsuperscript{16}

**Stretching protocols**

**Group 1: static stretching.**
Participants were asked to state which leg they usually used when kicking a ball. This was then defined as their dominant leg.

Starting position: the stretch was performed on the dominant leg with participants in the supine position on a non-adjusable treatment plinth, with the knee remaining in extension and the femur in neutral rotation. A lumbar roll was used to maintain participants' lumbopelvic lordosis in a neutral position throughout the test. The contralateral thigh remained completely in contact with the plinth, stabilized by a belt. The first author passively raised the

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**Figure 2.** Positioning of the Inclinometer for the measurement of straight leg raise test

**Figure 3.** The lower extremity was passively raised from the point of onset of resistance (R1) to the point of highest stretch tolerance as subjectively reported by the participant (P2). P2 was the limiting factor of the SLR. While resistance had appeared earlier in the stretch range, this was not the limiting factor (R').

AB represents normal range of motion of SLR.
R' is defined as increased resistance but not the limiting factor of SLR.
AC represents the intensity of perceived stretch tolerance.
BD is the end of SLR range (hamstring extensibility) and it is a broad, shaded area as the end of the range is not a distinct point.

**Secondary outcome:** Maximal perception of pain intensity at greatest stretch tolerance (end of SLR ROM) was determined via the use of a horizontal 10 centimeter visual analogue scale (VAS) with anchor points of 0 (no pain) and 10 (worst perceived pain). Participants were requested to mark the intensity of their perceived pain on the VAS using a pencil (P2). The VAS was chosen for measurement of pain because of its ease of administration and responsiveness.\textsuperscript{25} The level of pain measurements was taken at baseline, immediately after, and one-hour post-intervention.
10 seconds with a pillow under the knee; and thereafter measurement of SLR ROM and perceived pain intensity (stretch tolerance) at the new range was obtained.

**Group 2: dynamic oscillatory stretching**
Starting position: same as for SS.

The first author passively raised the leg to the point of the first sensation of a stretch. Each participant assisted the stretch by contracting his/her hip flexor muscles, while the knee extensors maintained the position of knee extension. Hip flexor and knee extensor contractions were sustained throughout the stretch. A two-second, slow passive stretch at the end of the range was applied to assist in further extending the stretch (Figure 5). The main investigator counted 101, 102 to standardize the two-second stretch. The agonist contraction was maintained throughout the stretch. This procedure was repeated 10 times over three sets. The lower extremity was stretched to a new point of tolerance with each set. The total stretching time was again 60 seconds: 2 sec x 10 repetitions x 3 sets.

For both stretching groups at the completion of the stretch, the lower extremity was allowed to rest for 10 seconds with a pillow under the knee; and thereafter measurement of SLR ROM and perceived pain intensity (stretch tolerance) at the new range was obtained.

**Group 3: placebo-control**
Participants in the placebo-control group received a one-minute sham ultrasound to the dorsal aspect of the foot in side lying. This procedure was chosen as a placebo due to the known absence of an anatomical and physiological relationship between the dorsum of the foot and the hamstrings muscle. Unfortunately, it is not possible to blind participants in studies of this kind. Although the control group might have realized they were not in the experimental group, the recruiting information stated that the study aimed to determine the effect of different interventions on hamstring extensibility.

**Statistical Analysis**
Homogeneity of group characteristics (age, height, body mass) was determined by one-way analysis of variance (ANOVA) and Tukey's post-hoc test. Shapiro-Wilk tests established the normal distribution of all data sets. Differences between interventions (DOS, SS, and control) for SLR and reported pain at three
The mean descriptive characteristics of the three experimental groups are presented in Table 1. There were no significant differences between groups. Changes in ROM during SLR are presented in Figure 6. There was a significant interaction effect (intervention x time) for ROM. SLR was not different between groups pre-intervention (Control 73 ± 12°, SS 79 ± 8°, DOS 76 ± 10°, p = 0.322). Immediately post-intervention, both SS, and DOS groups increased their ROM above the control group (Control 73 ± 12°, SS 86 ± 8°, DOS 94 ± 11°, p < 0.001). The increased ROM in DOS post-intervention was significantly greater than for SS (p < 0.001). One hour following intervention, there was no longer any difference in ROM between the control and SS groups, but ROM in the DOS group remained elevated above both other groups (Control 73 ± 12°, SS 80 ± 8°, DOS 89 ± 12°, p = 0.001).

Changes in most intense perceived pain at the end of the range of SLR (stretch tolerance) are presented in Figure 7. A significant interaction effect (intervention x time) was present for the self-reported pain measure. Pain at the end of the range of SLR was not significantly different between groups pre-intervention (Control 4.8 ± 1.1, SS 5.4 ± 0.8, DOS 5.7 ± 1.5 AU). Immediately post-intervention, the DOS and SS groups reported a similar perception of pain, however, this was significantly greater reported pain than for the control group (Control 4.3 ± 1.3, SS 5.9 ± 0.8, DOS 5.3 ± 1.3 AU, p < 0.001). This similar pain response, however, was achieved in the statistically significantly increased ROM seen in

![Table 1. Descriptive characteristics of 3 experimental groups (presented as group mean +/- standard deviation).](Image)

<table>
<thead>
<tr>
<th>Group</th>
<th>DOS</th>
<th>SS</th>
<th>Control</th>
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<tbody>
<tr>
<td>N (f/m)</td>
<td>20 (15/5)</td>
<td>20 (16/4)</td>
<td>20 (14/6)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>22 ± 1</td>
<td>22 ± 1</td>
<td>22 ± 1</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>70.9 ± 11.2</td>
<td>65.2 ± 10.9</td>
<td>68.0 ± 6.9</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.66 ± 0.8</td>
<td>1.64 ± 0.5</td>
<td>1.67 ± 0.4</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>26.1 ± 5.1</td>
<td>24.3 ± 4.5</td>
<td>24.3 ± 2.0</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SD. DOS = dynamic oscillatory stretch, SS = static stretch. N = number of participants in each group. (f/m) designates number of females and males. No significant differences were found between groups, p < 0.05. Statistical analysis was performed using Statistical Package for the Social Sciences (version 22, IBM.com).

**RESULTS**

The mean descriptive characteristics of the three experimental groups are presented in Table 1. There were no significant differences between groups. Changes in ROM during SLR are presented in Figure 6. There was a significant interaction effect (intervention x time) for ROM. SLR was not different between groups pre-intervention (Control 73 ± 12°, SS 79 ± 8°, DOS 76 ± 10°, p = 0.322). Immediately post-intervention, both SS, and DOS groups increased their ROM above the control group (Control 73 ± 12°, SS 86 ± 8°, DOS 94 ± 11°, p < 0.001). The increased ROM in DOS post-intervention was significantly greater than for SS (p < 0.001). One hour following intervention, there was no longer any difference in ROM between the control and SS groups, but ROM in the DOS group remained elevated above both other groups (Control 73 ± 12°, SS 80 ± 8°, DOS 89 ± 12°, p = 0.001).

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the spinal cord or in higher levels within the central nervous system. Wright argued that passive physiological oscillatory movements preferentially activate the descending inhibitory noradrenergic system and exert a hypoalgesic influence on the mechanical nociceptor. Given that musculoskeletal conditions appear to involve changes in mechanical nociceptors, it is possible that DOS, due to its similarity to the mechanism of passive physiological oscillatory techniques, could effectively promote pain tolerance and subsequently increase ROM. This study included only asymptomatic individuals, which raises the question of whether pain variables can be accurately measured via self-reporting in healthy individuals. The use of asymptomatic individuals is commonly reported in experimental pain studies utilizing quantitative sensory testing methodologies. These include mechanical pressure and experimentally induced pain with one study, like this study, measuring pain using VAS. Pain variables therefore, can be used accurately when measuring healthy individuals, but any conclusions drawn from the results of this study should be applied with caution.

Having dealt with the effect of DOS on stretch tolerance, attention can be turned to the effect of neural tissue mobilization on hamstring extensibility. Decreased hamstring extensibility as evidenced by the limited range in the SLR test could also be due to altered neurodynamics of the sciatic and tibial nerves. Changes in mechanosensitivity of the sciatic nerve have been shown to reduce hamstring length in asymptomatic individuals. Neural mobilization techniques alone and in combination with static stretch have been demonstrated to be effective in increasing hamstring extensibility in healthy volunteers. Nee and Butler hypothesized that “oscillatory movements can have a positive impact on symptoms by improving intraneural circulation, axoplasmic flow, and neural connective tissue viscoelasticity.” Altering mechanosensitivity of the posterior thigh neural system could be a plausible mechanism for increasing hamstring extensibility utilizing DOS. It is therefore suggested that neural tissue mobilization could play a significant role in improving stretch tolerance. Immediately post-intervention, the DOS, and SS groups reported similar pain scores as a measure of
stretch tolerance, but the DOS group had increased ROM. This might indicate that DOS could be more comfortably tolerated than SS. This is important because static stretching in a clinical setting can be painful. However, clinicians believe that its long-term benefits outweigh the short-term disadvantage of patient discomfort. Stretching techniques like DOS that have the capacity to modify stretch tolerance could be effective as a therapeutic stretch. This, however, requires further randomized studies on symptomatic individuals across a broader age group with longer follow-up, using stretching interventions that are effective at changing stretch tolerance. Therefore, the results of this study can be generalized only to a healthy, asymptomatic, young adult population. Enhanced understanding of the effect of stretching following the application of DOS, as a result of the findings of this study, will hopefully enable clinicians to provide more effective and scientifically-based treatment when incorporating stretching activities into rehabilitation programs.

This is the first study to investigate stretching utilizing dynamic oscillatory movement, with PNF and static stretching incorporated. The results of only one study have indicated that stretching is effective in achieving pain relief. That study however, included a combination of manual therapy and static stretch.

CONCLUSION
The results of the current study demonstrate that improvements in hamstring extensibility can be achieved with both DOS and SS techniques. Notably, DOS showed a superior increase in extensibility immediately and one-hour post-intervention while SS had lost the increased SLR one-hour post-intervention. DOS demonstrated an increase in stretch tolerance at the newly obtained range one-hour post-intervention. The dynamic oscillatory stretching technique used in the current study could provide clinicians with an effective therapeutic stretching option for increasing extensibility with good tolerance of the technique.

REFERENCES


ABSTRACT

Background: Idiopathic patellofemoral pain (PFP) has been linked to hip weakness and abnormal lower extremity mechanics. The effect of a strengthening intervention on balance has not been well studied among individuals with PFP.

Hypothesis/Purpose: The primary aim of this study was to evaluate changes in center of pressure displacement during the single limb squat following a nine-week physical therapy intervention among adolescent females with PFP.

Study Design: Interventional and cross-sectional

Methods: Seven adolescent females with PFP (10 extremities) were included in the study. Center of Pressure (CoP) excursions during a single limb squat task were measured before and after a nine week of physical therapy intervention focused on strengthening of the hip and core. Seven asymptomatic females were matched to the PFP group on the basis of age and activity level, and were tested as a reference group. CoP trajectories were reduced into four variables: mean distance (MDIST), root-mean-square distance (RDIST), range (RANGE), and 95% confidence interval circle area (AREA-CC). Maximum knee flexion angle, peak knee power generation and absorption were also recorded. Linear mixed models were used to test for within and between group differences in CoP metrics.

Results: Pre-intervention, CoP range, knee power absorption and generation were significantly decreased in the PFP group relative to the reference group. Post-intervention, the PFP group reported a significant decrease in symptom severity. There was also a significant (p<0.05) increase in MDIST, RDIST, RANGE, AREA-CC, peak knee flexion angle, peak knee power generation and absorption were also recorded. Linear mixed models were used to test for within and between group differences in CoP metrics.

Conclusion: Hip and core-strengthening resulted in a significant decrease in symptom severity as well as significant reductions in CoP displacement.

Level of Evidence: 3

Key words: Balance, hip strength, patellofemoral pain syndrome, postural stability
INTRODUCTION

Hip weakness and subsequent abnormal lower extremity mechanics may contribute to the development of Idiopathic Patellofemoral Pain (PFP).\(^1,2\)

Poor control of the femur during weight bearing tasks is believed to alter the kinematics of the knee joint, leading to joint dysfunction and pain.\(^3,5\) Furthermore, hip muscles are integral in proper lower extremity mechanics and are especially important during single limb tasks.\(^6\)

The single limb squat (SLS) has been used as an assessment of lower extremity mechanics and strength.\(^7\) Previous authors suggest adequate hip and core strength may help to minimize unnecessary femoral and pelvic motion during this task.\(^6\) Excessive motion of the trunk, pelvis and femur may make balance more challenging during any single limb support task, so measuring balance performance during the SLS may reveal proximal weakness and excessive compensatory movements during this maneuver.

Center of pressure (CoP) displacement during dynamic tasks has been used to assess balance and postural stability in many studies.\(^8-11\) For a task such as SLS, CoP measures may be used to evaluate how the subject prepares and responds to anticipated movements.\(^12,13\) The CoP represents the instantaneous point of application of the ground reaction force vector (GRF) in the plane of the supporting surface during weight bearing, and its time history or trajectory reflects a subject's ability to maintain balance. People may use different strategies to control their posture that may reflect their available strength, balance, coordination, and/or body mechanics.

The primary aim of this study was to evaluate changes in center of pressure displacement during the single limb squat following a nine-week physical therapy intervention among adolescent females with PFP. The authors hypothesized that a hip-strengthening intervention would result in changes in center of pressure displacement during a single limb squat task.

METHODS

Participant Selection

Seven young females between the ages of 12 and 18 diagnosed with PFP were recruited from our institution’s Sports Medicine Clinics. The inclusion criteria were unilateral or bilateral PFP without history of any prior acute trauma to the lower extremity, and a history of an insidious onset of activity related pain for one to six months during two or more of the following activities: exercise/athletics, prolonged sitting for greater than one hour, ascending/descending stairs, squatting or kneeling. The diagnosis of idiopathic patellofemoral pain was confirmed by a fellowship trained, board certified, pediatric sports medicine physician. In subjects with bilateral pain, both legs were tested. A total of 10 symptomatic legs (three subjects were affected by bilateral PFP and four subjects were affected by unilateral PFP) were included in the symptomatic group.

Based on the demographics of each subject in the symptomatic group, seven young females without any history of knee pathology and/or knee pain were individually recruited to serve as the reference group. For analysis, the reference subjects were matched to the symptomatic subjects on the basis of age (difference < seven months). For matching purposes, a total of 10 limbs were included in the reference group. Table 1 lists the descriptive characteristics of all subjects. The study was approved by the Colorado Multi-Institutional Review Board. All subjects and parents reviewed and signed an informed consent form before participating in any study related procedures.

Study Procedures

Symptomatic subjects reported to one of two sports medicine trained physical therapists (Sport Certified Specialists) for a comprehensive physical examination. During this visit, the symptomatic subjects were given an individualized exercise prescription and formal instruction on how to properly complete the home physical therapy program (Appendix 1). Completion of the physical therapy intervention consisted of progression from open kinetic chain exercises (3-4 times per week), to closed kinetic chain exercises (3-4 times per week), to functional exercises that emphasized dynamic hip and core movement patterns (3-4 times per week). All home based exercises were selected based on functional anatomy of muscle actions as well as their previous utilization in related research.\(^14,15\) The parameters of intensity and duration were derived from basic exercise physi-
ology principles with parameters for strengthening and neuromuscular adaptation.\textsuperscript{16} The repetitions/hold time, sets and frequency were individually prescribed for each patient by the PT. Progression was assessed and adjusted during a weekly physical therapy visit. The foundation of the intervention was adapted from a hip and core strengthening intervention initially described by Mascal and Powers.\textsuperscript{15}

Symptom severity and knee function were assessed with the Anterior Knee Pain Symptom Scale (AKPS), Visual Analogue Scale for Worst (VAS-W) and Visual Analogue Scale for Usual pain over the past week (VAS-U)\textsuperscript{17-19} at the time of their pre-testing assessment. Within two weeks of this assessment, subjects reported to our laboratory and performed a SLS on two Bertec strain gage force platforms (Model 4060-10). Subjects started the squat maneuver in a closed chain position with one foot on each force platform. Subjects were instructed to stand on one foot with arms in a self-selected position and at a self-selected tempo, squat down without losing balance to a comfortable degree of knee flexion, and then return to an upright position. During this task, the torso position was to remain vertical without forward trunk flexion, the foot was to remain flat on the force platform or as close to flat as possible, and subjects were not allowed to support themselves on any stationary fixture. All subjects were given a chance to practice this maneuver five times before data were collected during five complete repetitions. Due to concerns regarding pain intensity, subjects were only required to squat to tolerance. One complete repetition was defined as max knee extension to max knee extension. All trials in which a subject lost balance and subsequently put both feet down were excluded from the analysis.

The single limb squat task was selected because it simulates a common athletic position\textsuperscript{6} and because the increased knee flexion angles achieved during the task simulate movement patterns (stair ascent/descent) known to exacerbate knee pain symptoms. Proper execution of the task requires adequate lower extremity strength and neuromuscular control. Each individual subject's pattern of CoP displacement during the SLS represents their ability to maintain balance during a challenging, functional movement pattern.\textsuperscript{12,13}

Prior to testing, 14 mm diameter retroreflective markers were placed on lower extremity bony landmarks, identified by palpation by one physical therapist with greater than five years of experience in a clinical movement analysis laboratory. The marker set was a modified version of the Helen Hayes marker set that includes the ten lower extremity markers described by Kadaba et al \textsuperscript{20} in addition to markers (medial femoral condyle and medial malleolus) that were utilized during the static calibration trial only. Marker trajectory data were recorded at 120 Hz using a thirteen camera Vicon MX motion capture system. Analog data from the two Bertec force platforms were collected at a frequency of 1080Hz. Vicon Nexus™ was used to process all motion capture data and a conventional gait model (Vicon Plug-in-Gait™) was used to generate kinematics, kinetics and CoP, which were time normalized to the duration of the task. All kinetic measures were normalized to each subject's body weight. Data were then imported into a custom Matlab (The MathWorks Inc., Natwick, MA, USA) program, which extracted peak knee flexion, peak power absorption, peak power generation, and Center of Pressure trajectory during the SLS. For all subjects, the same motion capture system, testing procedure and, software programs and processes were used during evaluation of symptomatic subjects, pre- and post-intervention, and the reference group.

The CoP data were reduced according to the equations outlined by Prieto.\textsuperscript{21} In order to quantify the CoP movements during the task, the following four measures were used: Mean distance (MDIST): the average distance from the mean CoP; Root-mean-square distance (RDIST): the RMS distance from the mean CoP; Range (RANGE): the maximum distance

<table>
<thead>
<tr>
<th>Table 1. Characteristics of the participants</th>
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<td>Symptomatic Group</td>
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<tr>
<td>Age (yrs)</td>
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<td>Tegner Activity Level</td>
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<td>BMI (kg/m²)</td>
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between any two CoP locations; and 95% confidence interval circle area (AREA-CC): the area of a circle that contains approximately 95% of the distances from the mean CoP. All CoP measures were quantified using Matlab. For each of the CoP variables, the average value from the five trials was used for statistical analysis. Figure 1 shows a sample CoP trajectory from a single limb squat. The maximum knee flexion angle, maximum knee power absorption, and maximum knee power generation values achieved during each SLS trials were identified using a custom Matlab program. For each variable, the average value from the five trials was used for statistical analysis.

**STATISTICAL METHODS**

Paired, two-tailed, t-tests were used to compare demographics in the two groups as well as changes in VAS-U, VAS-W, and AKPS scores following the physical therapy intervention. A generalized linear regression analysis was used to compare within group (symptomatic group pre- vs. post-intervention) and between group (symptomatic group pre-intervention vs. reference group and symptomatic group post-intervention vs. reference group) differences in CoP measures, knee flexion angles, and knee power. When evaluating within group changes, the unstructured covariance structure was used to account for correlation due to repeated measures (pre- and post-intervention time points). Random intercept models were used to account for the correlation due to the inclusion of multiple limbs from the same subject.

All statistical analyses were performed using SAS version 9.3 (SAS Institute Inc., Cary, NC, USA)

**RESULTS**

The clinical characteristics associated with the symptomatic and reference groups are listed in Table 1. There was no difference (p>0.05) in age, activity level or BMI between the two groups. After the nine week hip-strengthening intervention, there was a significant decrease in average Anterior Knee Pain Symptom Scale (AKPS), Visual Analogue Scale for Worst Pain (VAS-W) and Visual Analogue Scale for Usual Pain (VAS-U) over the past week (Table 2). The clinical outcomes associated with the intervention (change in hip strength, hip kinematics and symptom severity) were not the focus of this study as they have been previously presented. Although the reduction in symptom severity was not the focus of this manuscript, it has been reported to context for the CoP measurements.

**Pre- vs. post-intervention changes in the symptomatic group**

Among subjects in the symptomatic group, there was a significant increase in the following CoP measures after the nine-week hip-strengthening intervention: AREA-CC (mean difference: 2012.88 mm², 95% CI: 170.31 to 3855.45; p = 0.0347), MDIST (mean difference: 2.72 mm, 95% CI: 0.23 to 5.21; p = 0.0347), RDIST (mean difference: 3.31 mm, 95% CI: 0.67 to 5.96; p = 0.0182) and RANGE (mean difference: 12.62 mm, 95% CI: 5.37 to 19.87; p = 0.0026). There

<table>
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<th>Table 2. Improvements in symptom severity following the intervention</th>
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<td>Mean Difference</td>
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<tr>
<td>AKPS</td>
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<td>VAS-W</td>
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<td>VAS-U</td>
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AKPS = Anterior knee pain scale; VAS-W = visual analogue scale for worst pain over the past week; VAS-U = visual analogue scale for usual pain over the past week.
was also a significant increase in peak knee flexion angle [mean difference: 8.04°, 95% CI: 4.25 to 11.84°, p = 0.0006], peak power generation [mean difference: 0.49 W/Kg], 95% CI: 0.21 to 0.78; p = 0.0025] and peak power absorption [mean difference: 0.49 W/Kg, 95% CI: 0.01 to 0.96, p = 0.044].

Reference group vs. symptomatic group

Prior to the intervention, peak power absorption, peak power generation and CoP range were significantly different between the symptomatic and reference groups. Peak power absorption during the single limb squat was an average of 0.92 W/Kg (95% CI: 0.45 to 1.38 W/Kg; p = 0.0029) higher in the reference group. Peak power generation was an average of 0.87 W/Kg (95% CI: 0.32 to 1.41 W/Kg, p = 0.0081) higher in the reference group. CoP range was higher in the reference group than the symptomatic group by an average of 7.73 mm (95% CI: 0.47 to 14.99, p = 0.0403). There was no significant difference in AREA-CC (p = 0.4162), MDIST (p = 0.1359), RDIST (p = 0.1066), or peak knee flexion angle (p = 0.8114).

Reference group vs. symptomatic group

After the physical therapy intervention, there was no significant difference in peak power absorption (p = 0.1019) peak power generation (p = 0.3324) or CoP range (p = 0.3708) between groups. Similarly, there was no significant difference between groups with respect to AREA-CC (p = 0.4057), MDIST (p = 0.4668), RDIST (p = 0.4967) or peak knee flexion angle (p = 0.2893). See Figures 2-3 for more information about the between and within group differences in peak knee flexion, peak knee power and the CoP measures.

DISCUSSION

CoP displacement, represents the subject’s response to internal and external perturbations during a given task. Compared to CoP measures during static tasks, CoP measures during dynamic tasks are a better discriminator of injured versus un-injured populations. Therefore, the primary purpose of this study was to assess CoP displacement during a single limb squat (SLS) among subjects with idiopathic PFP before and after a hip and core strengthening intervention. Following the nine-week intervention, the symptomatic group self-reported a significant reduction in symptom severity. The subjects also demonstrated a significant increase in CoP area, range, mean distance and root mean square distance. Together, these results provide some evidence that increased postural stability may be representative of a positive clinical outcome following PFP interventions.

Prior to the physical therapy intervention, the symptomatic subjects demonstrated a lower COP range relative to the reference group. Following the intervention, there was no longer a significant difference in CoP range between groups (Figure 2). The trend towards decreased CoP displacement among symptomatic subjects prior to the intervention contradicts the CoP measures reported by Lee et al in a case control study of subjects with and without PFP. In their study, subjects with PFP demonstrated significantly increased peak and mean medial-lateral CoP displacements during a single limb step-down task compared to the reference group. However, Lee et al used a metronome to control the cadence of the single limb task used in their study. By imposing a temporal constraint, the task demands are likely to change and thus, CoP excursions reported in the present study may not be directly comparable to CoP measures observed by Lee et al. Paterno et al assessed the biomechanics of 56 athletes that underwent anterior cruciate ligament reconstruction. Within 12 months of the evaluation, 13 (23%) of the athletes suffered a repeat ACL tear. Postural stability (average degree of deflection on the overall stability score as measured by the Biodex stability system), transverse plane hip moment, coronal plane knee range of motion, and sagittal plane knee moment were all significantly related to re-injury risk in the multivariable model. A deficit (increase) in unilateral postural sway during quiet standing was associated with increased likelihood of ACL re-injury (OR: 2.3, 95% CI: 1.1 to 4.7).

The results of the current study are consistent with a prospective study of a cohort of female soccer players. After controlling for other significant variables, Soderman et al demonstrated that a low postural sway was associated with a significantly greater risk for a lower extremity injury during the course of the soccer season. The design of the current study was unique in that CoP measures were evaluated before
Figure 2. Comparison of Variables Derived from CoP Measures.*Significantly (p < 0.05) different from post-intervention evaluation. **Significantly (P < 0.05) different from post-intervention evaluation and reference group.

Figure 3. Comparison of Peak Knee Power and Peak Knee Flexion.*Significantly (p < 0.05) different from post-intervention evaluation. **Significantly (P < 0.05) different from post-intervention evaluation and reference group.
and after a hip strengthening intervention. Following the nine-week intervention, dramatic improvements in the symptom severity were achieved according to the VAS-W, VAS-U and AKPS. Symptomatic relief was accompanied by a significant increase in CoP area, range, mean distance and root mean square distance. Increased CoP displacement following the intervention may be due to increased joint proprioception, due to an emphasis on hip and core strengthening during the intervention, and/or greater torque production at the hip joint. Along with improvements in stability, the subjects appeared to challenge themselves to a greater degree after the intervention. This was evidenced by an increase in peak knee flexion, peak knee power and peak knee absorption during the SLS. It is unclear, however, whether the changes in performance are due to improvements in neuromuscular control and strength or are due to the absence of pain during the task. Future research is needed to determine whether measures of CoP displacement such as area, range, MDIST, and RDIST are predictive of the onset of PFP in previously asymptomatic populations.

The peak (or maximum) knee flexion angle achieved during SLS is one of the measures used to subjectively evaluate symptomatic patients. Due to the fact that subjects with PFP routinely report the presence of pain during activities that involve increased knee flexion angles, such as stair ascent/descent, the authors of this study believe it is fair to assume that pain will limit the amount of knee flexion that is achieved during this task. Peak knee flexion angle was significantly higher in the reference group compared to the symptomatic subjects prior to the intervention suggesting that pain may have limited the magnitude of knee flexion observed among the symptomatic subjects. Following the physical therapy intervention, there were no significant differences in the knee flexion angles between the reference and symptomatic groups. This suggests that the symptomatic subjects may have returned to a more normal peak knee flexion angle after the intervention. Peak power generation and peak power absorption, on the other hand, were significantly higher in the reference group prior to the intervention and were not significantly different after the intervention between the groups. As power is calculated from joint torque and angular velocity, this suggests that the PFP subjects after the intervention were completing the task faster and/or with higher force. This supports the use of kinetic recordings to obtain metrics such as power and CoP displacement, rather than simply subjectively assessing knee joint angles.

There are several limitations to the study. Financial constraints limited the number of subjects the authors enrolled in this preliminary study. Comparisons of symptomatic and reference subjects were limited by the small sample size. Additionally, performance during single limb squat task was self-selected. Changes in postural stability following the intervention may have been related to the maximum knee flexion angle achieved during the task and/or changes in deceleration and acceleration during the downward and upward phases of the task, respectively. Future research should evaluate performance during a standardized version of the single limb squat test. Finally, individuals in the reference group were not re-tested and intervention was not randomized. It is not possible to assess causal relationship between hip therapy intervention, symptom severity, and increased postural stability. The possibility that changes in symptom severity and balance in the symptomatic group may have been due to greater familiarization with the task and/or the passing of time cannot be excluded based on this study alone.

**CONCLUSION**

At the beginning of this study, subjects with PFP demonstrated significantly decreased CoP range, peak knee power absorption and peak knee power generation relative to an asymptomatic reference group. Following a nine-week hip and core strengthening intervention, symptomatic improvements were accompanied by significant improvements in CoP excursions, peak knee power, and peak knee flexion angles. The results of the study suggest that changes in balance can be achieved in a population of subjects affected by PFP following a hip and core strengthening intervention. Furthermore, CoP measures may be an effective tool for assessing progression during a PT intervention designed to alleviate pain through improvements in lower extremity strength and neuromuscular control. Additional prospective cohort studies are needed to determine whether the CoP displacement measures used in this study during a single limb squat are also significantly predictive of the onset of PFP in previously asymptomatic populations.
REFERENCES:


14. Kendall FP. *Muscles: testing and function with posture and pain.* Baltimore, MD [etc.]: Lippincott Williams & Wilkins; 2010.


### Appendix 1. Individualized exercise prescription and progression by phases

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Description</th>
<th>Reps/Sets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Side Lying Abduction Leg Raise</strong></td>
<td>1. Lie on your side and straighten both hips and knees</td>
<td>Repeat ___ times per limb</td>
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<tr>
<td></td>
<td>2. Slowly raise your upper leg towards the ceiling (be sure to keep your leg in line with your body as you raise it towards the ceiling)</td>
<td>Perform ___ sets per session</td>
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<td></td>
<td>3. Return to the starting position</td>
<td></td>
</tr>
<tr>
<td><strong>Side Lying Hip Abduction and External Rotation (Clamshell)</strong></td>
<td>1. Lie on your side and bend your hips and knees</td>
<td>Repeat ___ times per limb</td>
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<tr>
<td></td>
<td>2. Slowly raise your upper leg towards the ceiling, rotating your knee outward (external rotation) as you raise your leg</td>
<td>Perform ___ sets per session</td>
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<td></td>
<td>3. Return to the starting position</td>
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<tr>
<td><strong>Prone Hip Extension with Bent Knee</strong></td>
<td>1. Lie on your stomach with one knee bent and one knee straight</td>
<td>Repeat ___ times per limb</td>
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<tr>
<td></td>
<td>2. Keeping your knee bent, lift your leg up and foot up towards the ceiling</td>
<td>Perform ___ sets per session</td>
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<tr>
<td></td>
<td>3. Hold this position without lifting your pelvis or rotating your leg</td>
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<td></td>
<td>4. Return to the starting position</td>
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<tr>
<td><strong>Single Leg Stand Wall Isometric</strong></td>
<td>1. Stand with your side next to a wall (parallel to the wall)</td>
<td>Repeat ___ times per limb</td>
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<tr>
<td></td>
<td>2. Lift the leg closest the wall so that your thigh is parallel with the ground and your knee is bent to 90 degrees</td>
<td>Perform ___ sets per session</td>
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<td></td>
<td>3. Keeping your body still, push against the wall with the outside of your bent knee</td>
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<td></td>
<td>4. Continue to push your knee against the wall for 10 seconds</td>
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<tr>
<td><strong>Quadriped Hip Abduction/External Rotation into Abduction</strong></td>
<td>1. Kneel on your hands and knees</td>
<td>Repeat ___ times per limb</td>
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<tr>
<td></td>
<td>2. Keeping your knee bent, rotate your leg towards the ceiling</td>
<td>Perform ___ sets per session</td>
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<td></td>
<td>3. Slowly straighten your knee and hip</td>
<td></td>
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<td></td>
<td>4. Slowly return to the starting position</td>
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<tr>
<td><strong>Band Resisted Lateral Walk</strong></td>
<td>1. Stand with a resistive band around both ankles</td>
<td>Repeat ___ times per session</td>
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<td></td>
<td>2. Slightly bend both knees</td>
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<td></td>
<td>3. Walk/shuffle sideways while you keep your hips, feet, and knees pointed forward</td>
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<tr>
<td><strong>Band Resisted Backward Diagonal Walk</strong></td>
<td>1. Stand with a resistive band around both ankles</td>
<td>Repeat ___ times per session</td>
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<tr>
<td></td>
<td>2. Slightly bend both knees</td>
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<td></td>
<td>3. Keeping your knees pointed straight ahead, walk backward by taking turns moving each foot in a diagonal, backwards direction</td>
<td>Perform ___ sets per session</td>
</tr>
<tr>
<td><strong>Excursions</strong></td>
<td>1. Stand on one leg with your knee slightly bent</td>
<td>Repeat ___ times per limb</td>
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<td></td>
<td>2. Maintaining your balance, bend forward at your hip</td>
<td>Perform ___ sets per session</td>
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<td>3. Reach your hand towards the floor in the directions outlined below</td>
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<td>4. Repeat for each of the arrows below</td>
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<td></td>
<td>5. Return to the starting position</td>
<td></td>
</tr>
<tr>
<td><strong>Bridge with Alternate Knee Extension</strong></td>
<td>1. Lie on your back with your hips and knees bent</td>
<td>Repeat ___ times per limb</td>
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<tr>
<td></td>
<td>2. Tense your abdominal muscles and lift your trunk upward so that your trunk, torso and thighs are in line</td>
<td>Perform ___ sets per session</td>
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<td></td>
<td>3. Hold this position and straighten one knee until it is fully extended</td>
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<td></td>
<td>4. Return your foot to the mat/floor and then lower your trunk to the mat/floor</td>
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### Appendix 1. Individualized exercise prescription and progression by phases (continued)

<table>
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<tr>
<th>Exercise</th>
<th>Description</th>
<th>Reps/Sets</th>
</tr>
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</table>
| **Anterior Diagonal Hip Strengthening** | 1. Secure one end of a resistance band to a table or railing  
2. Loop the other end around one ankle and move forward until the band is taught  
3. Keeping knee straight, push your foot forward and inward towards your other foot  
4. Pause and return to the starting position | Repeat ___ times per limb  
Perform ___ sets per session |
| **Posterior Diagonal Hip Strengthening** | 1. Secure one end of a resistance band to a table or railing  
2. Loop the other end around one ankle and move backwards until the band is taught.  
3. Keeping knee straight, pull your foot backwards and away from your other leg  
4. Pause and return to the starting position | Repeat ___ times per limb  
Perform ___ sets per session |
| **Squat with Band Resisted Hip Rotation and Abduction** | 1. Stand with a resistance band around your thighs, above your knees  
2. Squat down as if you are sitting back into a chair.  
3. As you are squatting down, push your thighs outwards against the resistance band | Repeat ___ times per limb  
Perform ___ sets per session |
| **Static Lunge with Band Resistance** | 1. Stand with one foot in front of the other in a lunge position  
2. Secure a resistance band around the thigh of your front leg, just above your knee so that the band slightly pulls your thigh towards your midline  
3. Bend both knees, dipping your body downwards towards the floor  
4. Keep your front knee centered over the ball of your foot and do not allow your front knee to move towards your midline | Repeat ___ times per limb  
Perform ___ sets per session |
| **Squat Jumps** | 1. Stand with your feet shoulder width apart  
2. Squat down as if you are sitting in a chair  
3. Jump straight up from the squat position  
4. During landing, bend your knees and hips back into the squat position | Repeat ___ times per limb  
Perform ___ sets per session |
| **Bridge with Alternate Knee Extension** | 1. Lie on your back with your hips and knees bent  
2. Tense your abdominal muscles and lift your trunk upward so that trunk, torso, and thighs are in line  
3. Hold this position and straighten one knee until it is fully extended.  
4. Return your foot to the mat/floor and then lower your trunk to the mat/floor | Repeat ___ times per limb  
Perform ___ sets per session |
| **Split Squats** | 1. Stand in a lunge position with one foot in front of the other  
2. Place the toe of your back foot on a step/stool/chair that it is at least 18 inches tall  
3. Bend both knees, dipping your body downwards towards the floor  
4. Keep your front knee centered over the ball of your foot and try to minimize side-to-side movements of your knee | Repeat ___ times per limb  
Perform ___ sets per session |
ABSTRACT

**Background:** Kettlebell (KB) and indian club swings (ICS) are used diversely for developing strength and power. It has been proposed that multiple swing techniques can be used interchangeably to elicit similar adaptations within performance training.

**Hypothesis/Purpose:** It was hypothesized that there will be not be a difference in peak joint angles between types of swings. Furthermore, given the nature of the overhead kettlebell swing (OKS), it was hypothesized that the OKS will be associated with a greater cycle time and a greater vertical impulse compared to shoulder height swing (SKS) and ICS. The purpose of this study was to analyze the kinematics and kinetics of the SKS, OKS, and ICS.

**Study Design:** Cross-sectional cohort

**Methods:** Fifteen healthy subjects underwent 3D biomechanical analysis for assessment of kinematic and kinetic data. Subjects performed two trials of ten repetitions at full effort for each swing in a randomized order using either a standard set of 0.45 kg indian clubs or sex specific KB loads (Female = 12kg, Male = 20kg). Lower extremity sagittal plane kinematics and kinetics were analyzed for peak values during the down and up portions of the swing patterns. Statistical analyses were carried out utilizing one-way ANOVAs ($p < .05$) and effect size indices.

**Results:** Cycle time for the OKS was 34% longer than the SKS and ICS ($p < .001$; ESI$_{SKS} = 2.09$, ESI$_{ICS} = 1.92$). In general, ankle (SKS: $0.82 \pm 0.16$; OKS: $0.90 \pm 0.21$; ICS: $0.60 \pm 0.15$ BW*BH) and hip joint moments (SKS: $2.34 \pm 0.68$; OKS: $2.32 \pm 0.53$; ICS: $1.84 \pm 0.47$ BW*BH) and joint powers, along with peak vertical ground reaction forces (vGRF) (SKS: $0.98 \pm 0.14$; OKS: $0.96 \pm 0.10$; ICS: $0.86 \pm 0.11$ BW/s), were higher in the SKS and OKS than the ICS ($p < .001$; ankle: ESI$_{SKS/OKS} = 0.43$, ESI$_{SKS/ICS} = 1.42$; hip: ESI$_{SKS/OKS} = 0.03$, ESI$_{SKS/ICS} = 0.87$; vGRF: ESI$_{SKS/OKS} = 1.80$, ESI$_{SKS/ICS} = 0.20$). There were no observed differences found in peak joint angles between the movements.

**Conclusion:** Although these swings are kinematically similar, the differing kinetic demands of these exercises may be important in selecting the right training modality for specific strength and power training.

**Level of Evidence:** 2

**Keywords:** Kettlebell training, power, resistance training, strength
INTRODUCTION
Strength and power are essential for athletic performance.1-6 Athletic tasks such as jumping require a high force production rate to enhance accomplishments.7 Allen et al.8 observed that increasing strength improved triple jump performance. Marian et al.9 concluded that eight weeks of power squat jump training increased maximal strength, vertical jump and sprint performance in recreational athletes. As a result, implementing strength and power training to enhance athletic development is ideal to augment athletic capabilities.4

Traditional strength and power training involves a large amount of space and equipment, requiring budgets up to 60,000 dollars per year.6 Many training facilities, however, only have modest space and resources6,10 with the average high school strength and conditioning facility having an average of 9.1 square feet per athlete.10 Furthermore, lower school enrollment has a direct correlation to budgetary concerns.6 Alternative training approaches may optimize space and financial limitations for strength and conditioning training.5,10,11 In response, performance specialists have focused on strength and power training requiring minimal equipment.12

In recent years, alternative training approaches to strength and power development have gained popularity; particularly the use of kettlebells (KB) and Indian clubs.12 The design of the KB and Indian club permits the center of mass to extend beyond the hand.3 As a result, this implement design is conducive for whole body ballistic movements; that are similar to the clean, snatch and jerk in traditional weightlifting.3 KB swings have been shown to help facilitate gains in strength, power and endurance.2,3,5,11,13 Lake and Lauder2 examined the effects of six weeks of KB or jump squat training on strength and power development. Both KB training and squat jump training were found to provide an increase of 9.8% and 19.8% in strength and power respectively, with no statistically significant differences between cohorts.2 In another study by Manocchia and colleagues3 investigating the transferability of KB training to other weightlifting exercises, a 10-week KB training cycle was shown to improve bench press by 14.2 kg and clean and jerk performance by 4.2 kg. These studies suggest the utility and transferability of KB training for the development of strength and power as compared to other more traditional methods.2,4,14

A common KB exercise is the shoulder height swing (SKS) (Figure 1: A, B).1,2,14,16 Previous authors14,15,17 have investigated the kinematics and kinetics of the SKS. Kim et al.17 observed that beginners demonstrated greater range of motion in the shoulders and different angular joint velocities compared to KB experts. McGill et al.14 concluded that the SKS exhibited loads to the lumbar spine that are in the opposite direction compared to the traditional deadlift. From the basic foundational principles of the SKS technique, the exercise can transform into various progressions. Two swing progressions that, to the authors' knowledge, have not been investigated within the literature are the overhead KB swing (OKS)18 and the Indian club swing (ICS).19 The OKS is a KB swing with the KB momentum ceasing at full shoulder flexion, and elbow extension (Figure 1 C, D).18 The ICS consists of two lightweight clubs, one held in each hand, positioned with the upper extremities in 90 degrees of shoulder abduction and elbow flexion, followed by upper limb horizontal adduction while initiating a hip hinge pattern (Figure 1: E, F).19 Previous research has assessed the transferability of KBS and ICS for the development of strength and power;20 however, there is little information in the literature regarding the different mechanical demands between the SKS, OKS and ICS.

In order to develop a better understanding of the different KB and IC training, this study examined the varying kinematic and kinetic demands of the different KB and IC swings. The purpose of this study was to analyze the kinematics and kinetics of the SKS, OKS, and ICS. Due to the parameters of the swings, it was hypothesized that no differences in peak joint kinematics would be found, (angles and velocities) which would suggest the swings are functionally similar. Furthermore, given the nature of the OKS, we hypothesize the OKS will be associated with a greater cycle time and a greater vertical impulse compared to SKS and ICS.

METHODS
To describe the mechanical demands of the SKS, OKS and ICS, 3D motion capture during a randomized exercise allocation was utilized.
Subjects
Fifteen healthy recreational athletes, consisting of nine males and six females ($n=15$; age, $26.7 \pm 4.3$ years; height, $1.76 \pm 0.09$ m; mass, $77.6 \pm 13.5$ kg) volunteered for this study. A convenience sample was employed to recruit subjects from the local university community. Inclusion criteria included that subjects reported no pain during the exercises, were free from injury in the prior six months and had at least six months of past experience with KB or indian club training. Exclusion criteria consisted of participants reporting pain currently or in the prior three months, an injury in the prior six months that limited participation in athletic activities, any surgery in the last 12 months, and those who had not received past KB or indian club instruction. All subjects were informed of the risks and benefits of the testing and written consent was obtained. The Duke University Health System Institutional Review Board approved this study. All data were collected and analyzed at the Michael W. Krzyzewski Human Performance Laboratory.

Kettlebell swing analysis
Participants were asked to wear spandex shorts and shirt and were given 10 minutes for instruction and warm-up prior to data collection. Participants were fitted with a modified Helen-Hayes marker set with a total of 48 retro-reflective markers placed on various anatomic landmarks (Figure 2). Three-dimensional marker coordinate data were captured using an eight camera motion capture system sampling at 120 Hz (Motion Analysis Corporation; Santa Rosa, CA), while embedded force plates (AMTI, Watertown, MA) sampling at 1200 Hz were used to collect tri-axial ground reaction forces. The retro-reflective markers were placed by the same investigator for each participant to limit interrater variability between data collections.

Before each movement, a single test administrator demonstrated each swing exercise and gave standardized minimal verbal cues. For all exercises, universal instruction consisted of instructing the patient to give full effort. SKS directions entailed swinging the KB to shoulder height. OKS directions were swinging the KB to the full overhead position, and ICS coaching focused on pulling the clubs behind the body. Full overhead position during the OKS was self determined by each subject due to each subject’s past KB experience. The ICS consisted of the athlete forcefully adducting the shoulders and

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**Figure 1.** Visual representation of the shoulder height kettlebell swing, (SKS: A, B) overhead kettlebell swing, (OKS: C, D) and indian club swing (ICS: E, F) during the down and up phases, respectively.
extending the elbows bilaterally, while concurrently initiating hip flexion and slight knee flexion. At this bottom position, the spine was held in neutral. The swing was reversed with the initiation of hip extension and bilateral shoulder abduction. The swing was completed when the Indian clubs were back to the original 90 degrees of shoulder abduction and the hips were slightly flexed. After each exercise trial, a volitionally determined rest break was given to each patient to minimize fatigue and preserve external validity to further mimic a training or rehabilitation setting. The medial instep of each foot was aligned vertically to the axilla to standardize stance width. Subjects performed two trials of 10 repetitions, at full effort for each swing type. To account for variations in trial initiation and completion, only the middle eight swings were used for analysis. Each subject used a standard set of 0.45 kg Indian clubs and sex specific KB’s (Female = 12 kg, Male = 20 kg). The sex specific KB masses were originally described by Pavel Tsatsouline in the Kettlebell Strong First Certification. Data were collected while subjects performed swing patterns with each foot on a separate force plate. Lower extremity sagittal plane kinematics and kinetics were analyzed during the down and up portion of the swing patterns.

Data Analysis
Coordinate data were filtered using a fourth-order low-pass Butterworth filter at 7Hz, and the ground reaction force data were filtered at 100Hz. Kinematic and kinetic data were calculated using Visual 3D (C-Motion, Bethesda, Maryland, USA). Joint angles were calculated as Cardan angles between segments with an order of sagittal plane, followed by frontal plane, and then transverse plane. Inverse dynamics were used to calculate joint moments, expressed as internal moments and normalized to mass and height. Ground reaction forces were normalized to and expressed as a percentage of body mass. The total cycle time for each swing was calculated from the peak of the vertical displacement of the motion to the subsequent vertical peak and averaged across swing type. To account for individual differences in timing of the swing cycle, each swing was normalized to the cycle time for analysis. Each variable of interest was extracted from these individual swings and averaged across swings and trials. Data were averaged between right and left limbs to account for slight variations in technique across participants. The six kinematic variables of interest included peak hip flexion, peak knee flexion, peak dorsiflexion, as well as the peak joint angular velocities at the hip, knee, and ankle (Table 1). The kinetic variables of interest included peak hip extension moment, peak knee extension moment, peak plantarflexion moment, peak hip extension power, peak knee extension power, peak ankle plantarflexion power, the peak vertical ground reaction force (vGRF), and vertical impulse before and after peak vGRF (Table 2). These dependent variables were calculated and extracted using custom software developed in Matlab R2010a (MathWorks Inc., Natick, MA).

Statistical Analysis
Statistical analyses were carried out using a series of one-way repeated-measures ANOVAs to assess differences between the SKS, OKS, and ICS. To account for increased Type I error from multiple comparisons, a conservative alpha was used ($\alpha = .01$). A Bonferroni adjustment considering the 15 total comparisons would result in a $p < .003$, which would
increase the probability of a Type II error. Tukey’s HSD post-hoc analysis was used to identify significant pairwise comparisons. Effect size indices (ESIs) were calculated in order to understand the clinical relevance that was not due to sample size. Statistical analyses were completed using SPSS 21 (SPSS Inc, IBM, Chicago, Illinois).

**RESULTS**

No significant differences were observed for peak ankle or knee angles across swing types. While no significant difference was observed in peak hip flexion angles, there was a small effect between SKS and ICS (ESI = 0.35) and OKS and ICS (ESI = 0.35). A small effect was exhibited in peak ankle plantarflexion velocity during the SKS compared to the OKS (ESI = 0.55), although this was not statistically significant. However, peak plantarflexion SKS velocity was greater than the ICS \( (p = .005; \text{ESI} = 0.75) \). Knee extension velocity was greater for the SKS compared to OKS \( (p = .003; \text{ESI} = 1.11) \) and OKS related to ICS \( (p = .003; \text{ESI} = 0.88) \). No differences were found between swing types for hip extension velocity; nevertheless there was a moderate effect between SKS and OKS \( (\text{ESI} = 0.52) \) and OKS and ICS \( (\text{ESI} = 0.69) \).

Cycle time for the SKS was significantly shorter than the OKS \( (p < .001; \text{ESI} = 2.09) \), while equal to the ICS \( (\text{ESI} = 0.05) \). The OKS cycle time was also greater than the ICS \( (p < .001; \text{ESI} = 1.92) \) (Table 1).

The vertical impulse before the peak vGRF, during the down portion of the swing, was smaller in the SKS compared to the OKS \( (p < .001; \text{ESI} = 1.80) \), which was greater than the ICS \( (p < .001; \text{ESI} = 1.23) \). The SKS and ICS vertical impulse prior to the peak vGRF were comparable \( (\text{ESI} = 0.20) \). The vertical impulse after peak vGRF was less in the SKS in relation to the OKS \( (p < .001; \text{ESI} = 1.14) \). The ICS displayed the least impulse after peak vGRF \( (p < .001; \text{ESI}_{\text{SKS}} = 2.00; \text{ESI}_{\text{OKS}} = 3.00) \). Unsurprisingly, the peak vGRF was greater in both the SKS and OKS \( (\text{ESI} = .17) \) when compared to the ICS \( (p < .001; \text{ESI}_{\text{SKS}} = 0.96; \text{ESI}_{\text{OKS}} = 0.95) \). Peak ankle plantarflexion moments were similar between the SKS and OKS; but displayed a moderate effect \( (\text{ESI} = 0.43) \). The SKS and OKS were both significantly greater than the ICS \( (p < .001; \text{ESI}_{\text{SKS}} = 1.42; \text{ESI}_{\text{OKS}} = 1.67) \). No significant differences were displayed in knee extension moment. Peak hip extension moment was similar between the SKS and OKS \( (\text{ESI} = 0.03) \), which were both larger than the ICS \( (p < .001; \text{ESI}_{\text{SKS}} = 0.87; \text{ESI}_{\text{OKS}} = 0.96) \). Similarly, peak ankle plantarflexion power was greater in the SKS and OKS \( (\text{ESI} = 0.15) \) compared to the ICS \( (p = .001; \text{ESI}_{\text{SKS}} = 2.82; \text{ESI}_{\text{OKS}} = 2.32) \). No significant difference

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**Table 1. Mean ± standard deviation, ANOVA and effect size index results for cycle time and kinematic variables of interest for each condition.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shoulder height kettlebell swing (SKS)</th>
<th>Overhead kettlebell swing (OKS)</th>
<th>Indian club swing (ICS)</th>
<th>( p )-value</th>
<th>( \text{ESI}_{\text{SKS}/\text{OKS}} )</th>
<th>( \text{ESI}_{\text{SKS}/\text{ICS}} )</th>
<th>( \text{ESI}_{\text{OKS}/\text{ICS}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak ankle dorsiflexion (deg)</td>
<td>11.3 ± 6.4</td>
<td>10.5 ± 6.5</td>
<td>9.7 ± 6.3</td>
<td>.385</td>
<td>0.12</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Peak knee flexion (deg)</td>
<td>60.8 ± 16.4</td>
<td>61.8 ± 16.2</td>
<td>62.2 ± 19.8</td>
<td>.787</td>
<td>0.06</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>Peak hip flexion (deg)</td>
<td>69.8 ± 9.3</td>
<td>69.7 ± 10.4</td>
<td>73.7 ± 12.8</td>
<td>.081</td>
<td>0.01</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>Peak ankle plantarflexion velocity (deg/s)</td>
<td>89.4 ± 32.8 *</td>
<td>72.2 ± 29.7 *</td>
<td>64.3 ± 33.9 *</td>
<td>.005</td>
<td>0.55</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>Peak knee extension velocity (deg/s)</td>
<td>257.3 ± 41.4 †</td>
<td>207.1 ± 49.0</td>
<td>252.1 ± 53.2 †</td>
<td>.003</td>
<td>1.11</td>
<td>0.11</td>
<td>0.88</td>
</tr>
<tr>
<td>Peak hip extension velocity (deg/s)</td>
<td>303.4 ± 66.2</td>
<td>270.5 ± 60.3</td>
<td>315.7 ± 70.1</td>
<td>.068</td>
<td>0.52</td>
<td>0.18</td>
<td>0.69</td>
</tr>
<tr>
<td>Cycle Time (s)</td>
<td>1.45 ± 0.16 †</td>
<td>1.92 ± 0.29</td>
<td>1.44 ± 0.21 †</td>
<td>&lt; .001</td>
<td>2.09</td>
<td>0.05</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Notes. \( p < .05 \) considered significant.  
† significantly different than OKS  
* all swings significantly different
was evident in peak knee extension power across the three swing types; however there was a moderate effect between the SKS and OKS (ESI = 0.60) and SKS and ICS (ESI = 0.35). Lastly, peak plantarflexion power was greater in the SKS and OKS (ESI=0.09) when compared to the ICS (p< .001; ESI_{SKS}=0.94; ESI_{OKS}=1.12)(Table 2).

**DISCUSSION**

Strength and power is essential for athletic performance.1,3-5,12 Developing strength and power through training methods that use minimal equipment is beneficial for space and budgetary demands.5,10,11 KB and indian club training are alternative methods in which to develop strength and power.12,19 As a result, understanding the different mechanical demands of varying KB and indian club exercises is necessary to select the proper training modality for desired adaptations.14,20 The purpose of this study was to analyze the mechanical demands imposed by SKS, OKS, and ICS. In support of the hypothesis, there were no differences in peak ankle or knee joint angles or hip extension velocity for the SKS, OKS or ICS. However, peak plantarflexion velocity was greater in the SKS compared to the OKS, which was greater than the ICS. The SKS displayed a decreased cycle time than the OKS, which was larger than the ICS. Contrary to the

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shoulder height kettlebell swing (SKS)</th>
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<th>Indian club swing (ICS)</th>
<th>p-value</th>
<th>ESI_{SKS/OKS}</th>
<th>ESI_{SKS/ICS}</th>
<th>ESI_{OKS/ICS}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Impulse prior to peak vGRF (BW*s)</td>
<td>0.43 ± 0.07 ¥ 0.61 ± 0.13 ¥ 0.45 ± 0.13 &lt; .001</td>
<td>1.80</td>
<td>0.2</td>
<td>1.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Impulse after peak vGRF (BW*s)</td>
<td>0.45 ± 0.09 * 0.57 ± 0.12 * 0.30 ± 0.06 * &lt; .001</td>
<td>1.14</td>
<td>2.00</td>
<td>3.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak vertical ground reaction force (BW)</td>
<td>0.98 ± 0.14 ¥ 0.96 ± 0.10 ¥ 0.86 ± 0.11 &lt; .001</td>
<td>0.17</td>
<td>0.96</td>
<td>0.95</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Peak ankle plantarflexion moment (BW*BH)</td>
<td>0.82 ± 0.16 ¥ 0.90 ± 0.21 ¥ 0.60 ± 0.15 &lt; .001</td>
<td>0.43</td>
<td>1.42</td>
<td>1.67</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Peak knee extension moment (BW*BH)</td>
<td>0.50 ± 0.36 0.47 ± 0.31 0.50 ± 0.37 .812</td>
<td>0.09</td>
<td>0.00</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak hip extension moment (BW*BH)</td>
<td>2.34 ± 0.68 ¥ 2.32 ± 0.53 ¥ 1.84 ± 0.47 &lt; .001</td>
<td>0.03</td>
<td>0.87</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak ankle plantarflexion power (BW*BH)</td>
<td>0.71 ± 0.24 ¥ 0.67 ± 0.28 ¥ 0.23 ± 0.10 &lt; .001</td>
<td>0.15</td>
<td>2.82</td>
<td>2.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak knee extension power (BW*BH)</td>
<td>1.36 ± 0.83 0.98 ± 0.44 1.09 ± 0.70 .522</td>
<td>0.60</td>
<td>0.35</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak hip extension power (BW*BH)</td>
<td>5.22 ± 2.18 ¥ 5.40 ± 1.92 ¥ 3.55 ± 1.39 &lt; .001</td>
<td>0.09</td>
<td>0.94</td>
<td>1.12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. p < .05 considered significant. BW = Body Weight, BH = Body Height ¥ significantly different than ICS; ° all swings significantly different

Table 2. Mean ± standard deviation, ANOVA and effect size index results for kinetic variables of interest for each condition.
hypothesis, the SKS and ICS displayed a bigger vertical impulse prior to peak vGRF in contrast to the OKS. However, in support of the hypothesis, the SKS and ICS had a decreased vertical impulse after peak vGRF in relation to OKS.

Consistent with the hypothesis, there were no significant differences in peak joint angles between any of the various swing types. This suggests the swings are mechanically similar and, given the similarities in the lowest positions, move through a comparable lower extremity range of motion. While not statistically significant, when variance was normalized, a moderate difference was observed in peak hip flexion between the KB swings (SKS and OKS) and ICS. While there are no studies to the authors’ knowledge investigating ICS, the greater peak hip flexion may be due to the specific techniques employed for the SKS, OKS and ICS. As previously described, the KB used in the SKS and OKS must pass between the knees to the bottom position. This is in contrast to the ICS, in which the Indian clubs project in a lateral downward path. From this trajectory, the hips may require increased range of motion, in order to allow the Indian clubs to effectively pass the without striking the body, compared to the KB swings. The SKS displayed similar peak plantarflexion velocity compared to the OKS, which were both greater than the ICS. The SKS was associated with greater peak knee extension velocity than the OKS, which had a lesser peak knee extension velocity in comparison to the ICS. The SKS and ICS had similar peak knee extension velocities. All three-swing variations displayed similar peak hip extension velocity. Future research is necessary in order to understand how different techniques employed by the KB and Indian clubs can affect kinematics at both the trunk and upper extremity.

Supporting the hypothesis, the SKS presented with a 34% lesser cycle time compared to the OKS, which was greater than and ICS, while the SKS and ICS displayed similar vertical impulse during the propulsion phase. Furthermore, the KB snatch integrates a more vertical trajectory to reach overhead, compared to the more curvilinear arc of the OKS. Lake and colleagues discerned that the KB snatch had greater vertical center of mass displacement (22 cm vs. 18 cm) compared to SKS. The bilateral OKS terminal position is similar to the unilateral KB snatch end point. With each swing beginning with a similar starting point, the OKS ending overhead caused a greater cycle time compared to the SKS and ICS. While this study did not investigate upper extremity and spine kinematics and kinetics during the OKS swing, future studies are needed to understand the role these body parts play due to the overhead requirements elicited during this KB swing pattern.

Unsurprisingly, the SKS exhibited less vertical impulse during the propulsion (up) phase when compared to the OKS, which was larger than and ICS, while the SKS and ICS displayed similar vertical impulse during the propulsion phase. Furthermore, the vertical impulse during the braking (down) phase of the SKS was less in relation to the OKS, while larger in contrast to the ICS. This is consistent with previous work and may be attributed to the larger amount of additional mass associated with the kettlebells as compared to the Indian clubs. In order to progress back to the standard KB swing bottom position; a decreased downward vertical displacement, and thus time, is required for the SKS and ICS when compared to the OKS. Previous authors have discussed the importance of impulse in regards to power production. Knudson has proposed that impulse establishes the degree and velocity of motion, and thus power is a non-optimal factor. Schilling et al. demonstrated that an increase in impulse resulted in greater velocities and force within squatting. As a result, for a fixed mass, a larger force or a longer time period for a given force will result in greater velocity. As a result, the vGRF is being absorbed over a shorter cycle time during the SKS or ICS in order to bring the KB or Indian clubs back to bottom position. This data suggests that while the SKS and OKS generate similar peak loads, the decreased SKS impulse created may be due to the shorter cycle time. The decreased cycle time observed in the SKS is associated with a
smaller amount of time under tension, which may elicit lower internal joint and tissue loads than OKS during the swing-braking (down) phase, while simultaneously generating similar peak loads as the OKS. The peak vGRF was similar between the SKS and OKS; which were both greater than ICS (Table 1). These findings support previous work of Lake and colleagues, in which the KB snatch and the SKS displayed similar vertical propulsion mean force values of 271.89 N and 291.37 N respectively. The OKS requires greater overhead mobility in order to proceed to terminal position, while the SKS and ICS proceed only to shoulder height. The similar peak vGRF observed between the SKS and OKS, suggests these swings require similar lower extremity force outputs to reach overhead and shoulder heights.

The SKS and OKS exhibited greater peak ankle plantarflexion moments and peak hip extension moments compared to the ICS. Similarly, the two KB swings (SKS and OKS) were associated with greater peak ankle plantarflexion and peak hip extension power production compared to the ICS. These findings are similar to those from Lake and Laudner's study, in which different KB swing types had comparable power outputs. Since all three swings displayed similar lower extremity joint excursion and hip extension velocities, the main component discrepancy between the KB swings and ICS is due to the force needed to propel the dissimilar weighted instruments, as displayed with the SKS and OKS demonstrating greater peak vertical vGRF compared to the ICS. The Indian clubs utilized within this study had a mass of 0.45 kg. This is in contrast to the 12 and 20 kg sex specific KB's employed for the SKS and OKS respectively. Unsurprisingly, these mass differentials required subjects to utilize more force during the SKS and OKS, and thus more power from the hip and plantarflexors compared to the ICS.

Future research is necessary in order to understand the effect past KB and Indian club training experience has on the proficiency of mechanical outputs.

**CONCLUSION**

In conclusion, while the SKS, OKS and ICS had overall similar mechanical characteristics; there were specific differences within each exercise. Specifically, the SKS exhibited a shorter cycle time and less downward and upwards-vertical impulse compared to the OKS. Furthermore, the SKS and OKS displayed greater peak moments and power from ankle plantarflexion and hip extension and greater vGRF compared to the ICS. This is the first study to compare kinematics and kinetics of the standard shoulder height kettlebell swing to the overhead kettlebell swing and the Indian club swing. Understanding the different mechanical demands of the SKS, OKS, and ICS can facilitate selecting an appropriate exercise for the desired strength and power training adaptation.

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ABSTRACT

Background: Two-dimensional motion analysis of lower-extremity movement typically focuses on the knee frontal plane projection angle, which considers the position of the femur and the tibia. A measure that includes the pelvis may provide a more comprehensive and accurate indicator of lower-extremity movement.

Hypothesis/Purpose: The purpose of the study was to describe the utility of a two-dimensional dynamic valgus index (DVI) in females with patellofemoral pain. The hypothesis was that the DVI would be more reliable and valid than the knee frontal plane projection angle, be greater in females with patellofemoral pain during a single-limb squat than in females without patellofemoral pain, and decrease in females with patellofemoral pain following instruction.

Study Design: Controlled Laboratory Study

Methods: Data were captured while participants performed single limb squats under two conditions: usual and corrected. Two-dimensional hip and knee angles and a DVI that combined the hip and knee angles were calculated. Three-dimensional sagittal, frontal, and transverse plane angles of the hip and knee and a DVI combining the frontal and transverse plane angles were calculated.

Results: The two-dimensional DVI demonstrated moderate reliability (ICC = 0.74). The correlation between the two-dimensional and three-dimensional DVIs was 0.635 (p < 0.001). Females with patellofemoral pain demonstrated a greater two-dimensional DVI (31.14° ± 13.36°) than females without patellofemoral pain (18.30° ± 14.97°; p = 0.010). Females with patellofemoral pain demonstrated a decreased DVI in the corrected (19.04° ± 13.70°) versus usual (31.14° ± 13.36°) condition (p = 0.001).

Conclusion: The DVI is a reliable and valid measure that may provide a more comprehensive assessment of lower-extremity movement patterns than the knee frontal plane projection angle in individuals with lower-extremity musculoskeletal pain problems.

Level of Evidence: 2b

Key Words: Frontal plane projection angle, movement, rehabilitation
INTRODUCTION

Lower-extremity musculoskeletal pain problems, including anterior cruciate ligament injuries, iliotibial band friction syndrome, and patellofemoral pain (PFP) may be associated with faulty movement patterns of the hip and knee. For this reason, movement patterns and the effect of movement retraining have been investigated, most often with three-dimensional (3D) motion analysis. Two-dimensional (2D) motion analysis, however, has become a more commonly utilized tool for answering clinical questions as it is cost-effective, available to clinicians, and less time intensive than 3D motion analysis. The reliability of 2D measures also has been reported to be acceptable with reliability values ranging from 0.59 to 0.98 depending on the 2D method, task analyzed, and type of reliability reported.

Three-dimensional and 2D motion analysis both have been utilized to assess an abnormal movement pattern often called dynamic knee valgus (Figure 1). Three-dimensional kinematic components of dynamic knee valgus have been quantified during single limb squat, providing insight into the contribution of hip adduction, knee medial rotation, knee adduction, and knee lateral rotation to the dynamic knee valgus movement pattern. Two-dimensional motion analysis, however, typically focuses solely on the knee using a knee frontal plane projection angle (FPPA; Figure 1). The knee FPPA visually appears to be knee abduction, although it is likely created by a combination of hip adduction, knee abduction, and knee lateral rotation that occurs during weight bearing knee flexion. The knee FPPA, while capturing the 2D orientation of the femur and tibia, may not accurately reflect the entire lower-extremity movement pattern, as 3D motion analysis does, because the pelvis' contribution to the lower extremity movement pattern is not taken into account. Pelvic drop may contribute to a hip adducted position. Noehren et al reported a greater hip adduction position in individuals with iliotibial band friction syndrome, suggesting the adducted position led to increased tension on the lateral structures of the knee, resulting in pain. Takacs and Hunt and Dunphy et al reported increased knee adduction moments in individuals who demonstrated contralateral hip drop without concomitant ipsilateral trunk lean. A more adducted position of the hip or increased knee adduction moment may alter or increase the stress to the patellofemoral joint, thus contributing to PFP. Knowledge of the pelvis' contribution to hip motion during a particular task may provide important information about different movement strategies used by individuals to accomplish a task. Furthermore, because people may present with varying degrees of hip and knee angles that contribute to the pain problem, a 2D variable that combines the hip and knee angles may be a more comprehensive representation of the entire lower-extremity movement pattern than the knee FPPA alone.

To the authors' knowledge, a hip and knee combined variable has not previously been reported. Therefore, the purpose of the current study was to describe the utility of a dynamic valgus index (DVI) in females with PFP. The authors hypothesized that the 2D DVI (1) would be more reliable and valid than the knee FPPA in the current study.
(2) would be greater in females with PFP during a single-limb squat compared to females without PFP, and (3) would decrease in females with PFP following within-session verbal instruction. Identifying a 2D variable that is potentially more comprehensive, reliable, and valid than the knee FPPA may result in a measure that more accurately reflects the entire lower-extremity movement pattern and lead to better identification and treatment of lower-extremity movement impairments. Furthermore, demonstrating successful utility of a comprehensive 2D variable provides additional support for the use of 2D measures during clinical assessment and to answer clinical questions related to lower-extremity movement impairments in individuals with musculoskeletal pain problems, particularly active individuals.

**METHODS**

**Participants**

Twenty women with chronic PFP and 16 women without PFP participated. Chronic PFP was defined as pain located at the patellofemoral articulation (behind or around the patella) of at least two months duration. To be included in the study, average pain reported for the prior week had to be a minimum of 3/10 using a verbal pain rating scale (0 representing no pain, 10 representing severe pain). Pain also had to be reproduced by at least two of the following tests: resisted isometric quadriceps contraction performed with the knee in approximately 10° of flexion, squatting, prolonged sitting, and stair ascent or descent. Females with PFP also had to demonstrate observable dynamic knee valgus during single limb squat. Observable dynamic knee valgus was defined as a visual frontal plane knee angle increase of 10° or more during the descent phase of the single limb squat test. Females without PFP qualified for the study if they had no history or current report of PFP and did not demonstrate an observable dynamic knee valgus during a single-limb squat. Exclusion criteria for both groups included (1) body mass index greater than 30 kg/m², (2) history of knee ligament, tendon, or cartilage injury; traumatic patellar dislocation; patellar instability; or prior knee surgery, (3) known pregnancy, and (4) neurological involvement that would influence balance and coordination during kinematic testing. Saint Louis University’s Institutional Review Board approved the study protocol and informed consent. All federal and state regulations for the protection of human participants were followed, as were the guidelines of the Declaration of Helsinki. Prior to participation in the study, all participants read and signed the informed consent.

**Kinematic Assessment**

Two-dimensional and 3D data were captured simultaneously while participants completed single limb squats under two conditions: usual and corrected. Single limb squat was performed because it is often pain provoking and likely to induce dynamic knee valgus. Participants with PFP performed the squats on their involved limb. Participants without PFP were randomly assigned to perform the squat on their right or left leg. All participants completed trials using their usual method first. For the usual trials, participants were instructed to keep their trunk straight and arms at their side while bending their knee to at least 60° (visually confirmed by investigator). No additional instructions were given about the position of the knee relative to the hip or foot. During the corrected trials, participants repeated the single limb squat with additional instructions. Participants were instructed to “keep your knee over the middle of your foot (don’t let your knee fall in)” during the descent phase of the squat. The corrected squat was demonstrated to the participants before they were allowed to practice the task. For both conditions, participants were allowed several practice trials prior to data collection to become comfortable with the task. Three trials were collected for the usual and corrected conditions; the average of three trials was used for data analysis.

Two-dimensional data were captured with a Sony DCR-HC96 HandyCam camcorder (Sony Corporation of America, Park Ridge, NJ, USA). The camera was positioned at a height of 45 cm, 3 meters anterior to the participant. Data were processed with Dartfish ProSuite 7 (Dartfish, Switzerland). All 2D angles (Figure 1) were measured from a frontal plane view by one investigator blinded to condition. A line drawn between markers placed on the anterior superior iliac spines defined the pelvic segment. A line drawn from the midpoint of the knee, bisecting the thigh, defined the thigh segment. A line drawn from the midpoint of the knee to the midpoint of the
ankle defined the shank segment. For each trial, hip and knee angles were obtained at peak knee flexion determined visually by the investigator. The knee FPPA angle was calculated as 180° minus the angle between the thigh segment and the shank segment (Figure 1a). A positive knee FPPA angle indicated apparent knee abduction. The hip FPPA was calculated as 90° minus the angle between the pelvis segment and the thigh segment (Figure 1a). A positive hip FPPA indicated apparent hip adduction. The 2D DVI was calculated as the sum of the hip and the knee FPPAs.

Three-dimensional data were captured with an 8-camera motional analysis system (Vicon, Oxford Metrics LTD. Oxford, England) sampled at 120 Hz. Data were captured and processed using previously described methods.

Prior to data collection, reflective markers were placed over the second sacral vertebrae, bilateral iliac crests, anterior superior iliac spines, medial and lateral femoral epicondyles, medial and lateral malleoli, calcaneus, lateral midfoot, anterior midfoot, and 1st and 5th metatarsal heads. Thermplastic shells with four reflective markers were placed on the lateral mid-thigh and lateral mid shanks. Data captured from these markers were processed using Visual3D® software (C-Motion, Inc., Rockville, MD, USA). Marker trajectories were low-pass filtered using a 4th-order Butterworth filter with a 6 Hz cutoff frequency. A six degrees of freedom model incorporating the pelvis (CODA model, Charnwood Dynamics Ldt., UK), thigh, shank, and foot was used for data processing. Hip and knee angles in the sagittal, frontal, and transverse planes were calculated and expressed in the reference frame of the proximal segment. For each trial, hip and knee angles were obtained at peak knee flexion determined by the Visual3D® software. The 3D DVI was the sum of hip and knee frontal and transverse plane angles, where hip adduction, hip medial rotation, knee abduction, and knee lateral rotation were considered positive values. The ICC3,1 (0.81-0.98) and SEM (1.0-3.5°) values for the trial-to-trial variability of 3D hip and knee angles have been reported previously.

**STATISTICAL METHODS**

Data were analyzed with IBM SPSS Statistics version 20 (SPSS, Chicago, IL, USA).

Intra-rater reliability of Dartfish measurements for repeated measures of hip and knee FPPAs completed a minimum of five days apart was assessed with intraclass correlation coefficients (ICC2,1). Inter-rater reliability of Dartfish measurements for hip and knee FPPAs, completed on a smaller sample by two individuals was assessed with intraclass correlation coefficients (ICC2,1).

Trial-to-trial within-session error for the 2D hip and knee FPPAs across the three trials was assessed by calculating ICC3,1 and standard error of the measure (standard deviation * √(1-ICC3,1)). Pearson product-moment correlation coefficients were calculated to examine concurrent validity between 2D and 3D variables captured during the usual condition. Independent samples t-tests were used to compare group differences in participant characteristics, peak knee flexion, knee FPPA, hip FPPA, and dynamic valgus indices in the usual condition. Paired t-tests were used to analyze differences between the usual condition and the corrected condition in participants with PFP. The alpha level was set at 0.05 for all statistical tests.

**RESULTS**

There were no group differences in age (mean ± SD; PFP: 22.4 ± 4.3 years, no PFP: 21.6 ± 3.0 years; \( P = 0.544 \)), BMI (mean ± SD; PFP: 22.4 ± 3.2 kg/m², no PFP: 22.7 ± 2.8 kg/m²; \( P = 0.678 \)), or angle of peak knee flexion during the usual condition (mean ± SD; PFP: 70.0° ± 7.49°, no PFP: 68.3° ± 6.6°; \( P = 0.484 \)). There also was no difference in peak knee flexion between conditions in females with PFP (mean ± SD; usual: 70.0° ± 7.49°, corrected: 66.9° ± 8.5°; \( P = 0.86 \)).

**Reliability**

The intra-rater reliability ICC2,1 of Dartfish measurements for repeated measures of hip and knee FPPAs completed a minimum of five days apart was 0.99. The inter-rater reliability ICC2,1 of Dartfish measurements for hip and knee FPPAs, completed on a smaller sample by two individuals was 0.97 for the hip FPPA and 0.99 for the knee FPPA. Trial-to-trial within-session variability ICC3,1 values ranged from 0.68-0.83 (Knee FPPA: 0.68, DVI: 0.74, Hip FPPA: 0.83) for 2D measures in the usual condition with standard error of the measures ranging from 3.29° to 8.63° (Table 1).
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**Table 1.** Intraclass correlation coefficients for trial-to-trial variability, and standard error of the measure for two-dimensional hip and knee variables.

<table>
<thead>
<tr>
<th></th>
<th>ICC$_{3,1}$</th>
<th>SEM</th>
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<tbody>
<tr>
<td>Hip frontal plane projection angle</td>
<td>0.83</td>
<td>3.29°</td>
</tr>
<tr>
<td>Knee frontal plane projection angle</td>
<td>0.68</td>
<td>5.80°</td>
</tr>
<tr>
<td>Dynamic valgus index</td>
<td>0.74</td>
<td>8.63°</td>
</tr>
</tbody>
</table>

ICC= intraclass correlation coefficient; SEM= standard error of the measure

**Table 2.** Correlations between two-dimensional and three-dimensional variables in the usual condition.

<table>
<thead>
<tr>
<th></th>
<th>Hip FPPA</th>
<th>Knee FPPA</th>
<th>2D DVI</th>
</tr>
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<tbody>
<tr>
<td>3D Hip Adduction</td>
<td>0.825‡</td>
<td>0.419*</td>
<td>0.661‡</td>
</tr>
<tr>
<td>3D Hip Medial Rotation</td>
<td>0.313</td>
<td>0.303</td>
<td>0.336*</td>
</tr>
<tr>
<td>3D Knee Abduction</td>
<td>0.250</td>
<td>0.036</td>
<td>0.103</td>
</tr>
<tr>
<td>3D Knee Lateral Rotation</td>
<td>0.415*</td>
<td>0.365*</td>
<td>0.425*</td>
</tr>
<tr>
<td>3D DVI</td>
<td>0.627‡</td>
<td>0.541†</td>
<td>0.635†</td>
</tr>
</tbody>
</table>

FPPA= frontal plane projection angle, 2D= two-dimensional, 3D= three-dimensional, DVI= dynamic valgus index. *p<0.05, †p<0.01, ‡p<0.001

**Concurrent validity**

The 2D measures of hip and knee kinematics demonstrated fair to excellent concurrent validity when compared to 3D kinematic measures (Table 2). The 2D DVI was positively correlated with 3D hip adduction, hip medial rotation, knee lateral rotation, and the 3D DVI. The hip and knee FPPAs were positively correlated with 3D hip adduction, 3D knee lateral rotation, and the 3D DVI. The correlations between the 2D DVI and all of the 3D variables were greater than the correlations between the knee FPPA and the 3D variables.

**Comparison between groups**

Females with PFP demonstrated a greater 2D DVI (mean ± SD; 31.14° ± 13.36°) than females without PFP (mean ± SD; 18.30° ± 14.97°; P=0.010; Table 3). The components of the 2D DVI also were different between groups. Females with PFP demonstrated a greater hip FPPA (mean ± SD; 19.66° ± 7.70°) than females without PFP (mean ± SD; 14.15° ± 6.53°; P=0.030; Table 3). Females with PFP also demonstrated a greater knee FPPA (mean ± SD; 11.48° ± 7.45°) than females without PFP (mean ± SD; 4.14° ± 7.62°; P=0.014; Table 3).

**Comparison between conditions**

Females with PFP demonstrated decreased dynamic valgus indices (mean ± SD; 2D DVI _Usual_ Condition: 31.14° ± 13.36°, _Corrected_ Condition: 19.04° ± 13.70°; P=0.001), as well as hip (mean ± SD; _Usual_ Condition: 19.66° ± 7.70°, _Corrected_ Condition: 14.48° ± 7.48°; P<0.001) and knee FPPAs (mean ± SD; _Usual_ Condition: 11.48° ± 7.45°, _Corrected_ Condition: 4.56° ± 7.48°; P=0.003) following
The DVI is a reliable and valid measure. The DVI demonstrated moderate trial-to-trial reliability, consistent with, or better than reliability of the knee FPPA reported previously in the literature and in the current study. Willson et al reported within-day reliability of the knee FPPA to be 0.88 during a single limb squat. Munro et al reported ICC values between 0.59 and 0.88 for the knee FPPA during different lower extremity tasks; the ICC value for single limb squat in females was reported to be 0.59. Using similar methods for measuring the knee FPPA, Herrington reported a reliability of 0.72 for the knee FPPA during a single limb squat.

The concurrent validity of the DVI during single limb squat also was consistent with or better than the concurrent validity of the knee FPPA reported in the current study and previously in the literature, when using similar methods. Willson et al reported correlations between the 2D knee FPPA and 3D segmental rotations of the pelvis, femur, and

<table>
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<th>Table 3. Between groups and between conditions comparisons of variables.</th>
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<tr>
<td>Females without PFP, Usual Condition*</td>
</tr>
<tr>
<td>Hip FPPA</td>
</tr>
<tr>
<td>Knee FPPA</td>
</tr>
<tr>
<td>2D DVI</td>
</tr>
<tr>
<td>3D DVI</td>
</tr>
</tbody>
</table>

FPPA= frontal plane projection angle; 2D= two-dimensional; 3D= three-dimensional; DVI= dynamic valgus index; PFP= patellofemoral pain

* Data presented as mean ± SD
† Data presented as mean group difference (95% confidence interval)
‡ Data presented as mean difference between conditions (95% confidence interval)

verbal instruction (Table 3). Females without PFP did complete the corrected trials. However, because they did not demonstrate observable dynamic knee valgus during single-leg squat, it was not expected the movement would change with cuing. Consistent with this hypothesis, there was no statistically significant change in any of the variables in females without PFP (p>0.05 for all comparisons).

DISCUSSION

The purpose of the current study was to describe the utility of a DVI in females with PFP. The authors hypothesized that the 2D DVI (1) would be more reliable and valid than the knee FPPA, (2) would be greater in females with PFP during a single-limb squat compared to females without PFP, and (3) would decrease in females with PFP following within-session verbal instruction. The results of the current study suggest the DVI may be an important variable to consider when examining lower-extremity movement patterns.

The DVI is a reliable and valid measure. The DVI demonstrated moderate trial-to-trial reliability, consistent with, or better than reliability of the knee FPPA reported previously in the literature and in the current study. Willson et al reported within-day reliability of the knee FPPA to be 0.88 during a single limb squat. Munro et al reported ICC values between 0.59 and 0.88 for the knee FPPA during different lower extremity tasks; the ICC value for single limb squat in females was reported to be 0.59. Using similar methods for measuring the knee FPPA, Herrington reported a reliability of 0.72 for the knee FPPA during a single limb squat.

The concurrent validity of the DVI during single limb squat also was consistent with or better than the concurrent validity of the knee FPPA reported in the current study and previously in the literature, when using similar methods. Willson et al reported correlations between the 2D knee FPPA and 3D segmental rotations of the pelvis, femur, and
tibia to range between 0.01 and 0.61. The highest correlation reported by Willson et al. was between the knee FPPA and the femoral adduction. This is consistent with the current study where the highest correlation between the 2D DVI and a 3D variable also was hip adduction.

Females with PFP demonstrated a greater 2D DVI than females without PFP. Females with PFP also demonstrated a greater knee FPPA than females without PFP, consistent with the findings of Willson et al., who reported a 4.1° difference in the knee FPPA between females with and females without PFP. The knee FPPA, however, does not capture the position of the pelvis, thus does not capture all movement that potentially contributes to stress at the knee. Pelvic position, however, could contribute to additional stress at the knee through different mechanisms. First, contralateral pelvic drop may increase lateral tension on the structures of the knee via the stretch of the tensor fascia latae/iliotibial band across the hip and knee. Noehren et al. reported individuals with iliotibial band friction syndrome demonstrated greater hip adduction during the stance phase of running, suggesting the adducted hip position led to increased tension on lateral structures of the knee, resulting in pain. Similarly, an adducted position of the hip could result in tension on the lateral structures of the knee, affecting patellar alignment, leading to PFP. Second, contralateral pelvic drop without concomitant ipsilateral trunk lean results in a medial shift of the line of gravity, which increases the knee adductor moment. Takacs and Hunt and Dunphy et al. reported increased knee adduction moments in individuals who demonstrate contralateral hip drop without concomitant ipsilateral trunk lean when compared to individuals who do not demonstrate contralateral hip drop. The increase in knee adduction moment may alter the stress distribution on the patellofemoral joint, potentially contributing to PFP. Assessment of the DVI, which captures positioning of the tibia, femur, and pelvis, may provide important, comprehensive information about different movement strategies used to accomplish a task and contribute to the pain problem.

Females with PFP also demonstrated a decrease in the DVI following verbal instruction targeting the knee position. Prior to the current study, the ability of 2D measures to detect change in multi-joint movement patterns in females with PFP was unclear. Olson et al. reported that 2D methods were sensitive enough to detect changes in the knee FPPA following a 4-week neuromuscular retraining program. However, only healthy females were examined and only the knee FPPA was quantified. The current study, which detected changes in hip and knee FPPAs, as well as the 2D DVI in females with PFP following verbal instruction confirms the potential for 2D methods to be used as a research and clinical tool to examine changes in both hip and knee movement patterns in clinical populations. Both the hip and knee FPPAs decreased following instruction, but, consistent with the instruction provided, there was a greater decrease in the knee FPPA than the hip FPPA. Additional instruction targeting pelvic position may result in a greater decrease in the DVI. Further research is necessary to explore cueing of the pelvis and knee when the faulty movement pattern includes poor pelvic position.

The current study has limitations. The 2D data was captured as part of a larger 3D study; the methods for 2D motion capture may have been less precise resulting in increased error. Better positioning of the camera for 2D data collection would likely decrease some error. In the current study, however any error created by camera placement was systematic across all participants. A second limitation is that the current data is from a small sample of females performing the single-limb squat. The information may not be generalizable to a larger sample of a different population or task. Further research is necessary to explore the importance of examining the DVI with other tasks and populations.

CONCLUSION
The DVI combines 2D motion analysis of the hip and the knee, creating a more comprehensive 2D assessment of lower-extremity movement than the 2D knee FPPA alone. The DVI is reliable, valid, can discriminate between groups, and is sensitive to change. The successful utility of the DVI in the current study provides additional support for the use of 2D measures during clinical assessment and to answer clinical questions related to lower-extremity movement impairments in individuals with musculoskeletal pain problems, particularly active individuals.
REFERENCES


ABSTRACT

Background: Only a small amount of evidence exists linking hip abductor weakness to dynamic knee valgus during static and dynamic activities. The associations of hip extensor strength and hip kinematics during the landing of a single leg hop are not known.

Purpose: To determine if relationships exist between hip extensor and abductor strength and hip kinematics in both involved and uninvolved limb during the landing phase of a single leg hop in recreational athletes post anterior cruciate ligament (ACL) reconstruction. The presence of similar associations was also evaluated in healthy recreational athletes.

Study Design: Controlled Laboratory Study; Cross-sectional

Methods: Twenty-four recreational college-aged athletes participated in the study (12 post ACL reconstruction; 12 healthy controls). Sagittal and frontal plane hip kinematic data were collected for five trials during the landing of a single leg hop. Hip extensor and abductor isometric force production was measured using a hand-held dynamometer and normalized to participants' height and weight. Dependent and independent t-tests were used to analyze for any potential differences in hip strength or kinematics within and between groups, respectively. Pearson’s r was used to demonstrate potential associations between hip strength and hip kinematics for both limbs in the ACL group and the right limb in the healthy control group.

Results: Independent t-tests revealed that participants post ACL reconstruction exhibited less hip extensor strength (0.18 N/Ht*BW vs. 0.25 N/Ht*BW, p = < .01) and landed with greater hip adduction (9.0° vs. 0.8°, p = < .01) compared with their healthy counterparts. In the ACL group, Pearson’s r demonstrated a moderate and indirect relationship (r = -.62, p = .03) between hip extensor strength and maximum hip abduction/adduction angle in the involved limb. A moderate and direct relationship between hip abductor strength and maximum hip flexion angle was demonstrated in the both the involved (r = .62) and uninvolved limb (r = .65, p = .02). No significant associations were demonstrated between hip extensor or abductor strength and hip flexion and/or abduction/adduction angles in the healthy group.

Conclusion: The results suggest that hip extensors may play a role in minimizing hip adduction in the involved limb while the hip abductors seem to play a role in facilitating hip flexion during the landing phase of a single leg hop for both limbs following ACL reconstruction. Researchers and clinicians alike should consider the importance of the hip extensors in playing a more prominent role in contributing to frontal plane motion.

Levels of Evidence: Level 2a

Keywords: ACL reconstruction, hip strength, kinematics, single leg hop

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This study was approved by the Institutional Review Board at the University of Tennessee at Chattanooga on 09/18/2014 (#14-112).

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INTRODUCTION
An estimated 200,000 people suffer an anterior cruciate ligament (ACL) injury each year. Further evidence suggests that only 70% will return back to their previous level of function. For those that do return to sport, approximately 30% will be at risk of suffering a subsequent ACL injury to either the contralateral limb or ipsilateral limb. The majority of ACL injuries have been attributed to noncontact mechanisms during sudden decelerations and jump-landings. Risk factors associated with noncontact ACL injuries have been classified as environmental, anatomical, hormonal, or biomechanical. Of these four risk factors, biomechanical factors have received the most attention since they are likely the easiest to change through neuromuscular training. In particular, excessive knee valgus during dynamic activities involving jump-landings and cutting has received the most attention due to its link to ACL (re)injury.

A recent evidence-based review has highlighted the value of hip-specific neuromuscular exercise interventions that are capable of modifying dynamic knee valgus in efforts to prevent anterior cruciate ligament (ACL) injuries. Separate studies by Lee and Nadler demonstrated that female athletes who experienced lower extremity injury were more likely to demonstrate decreased hip strength. Howard et al demonstrated that weakness of the hip abductors and external rotators was associated with increased knee valgus during single-leg landing tasks. This line of research has shown a possible association between weak hip abductors and excessive valgus motion at the knee. However, a recent systematic review demonstrated only a small amount of evidence linking hip abductor weakness to dynamic knee valgus. Previous studies tended to only analyze either hip abductor and/or external rotator strength. Therefore, researchers and clinicians alike may have focused primarily on hip abductor and external rotator strength and overlooked the capability of the hip extensors to provide dynamic stability within the frontal plane. For this reason, it would be of interest to know if potential associations between hip extensor strength and hip kinematics exist during dynamic movements in individuals who have undergone ACL reconstruction as well as healthy athletes.

The single leg hop test is frequently used by clinicians to assess functional performance after ACL reconstruction to determine readiness to return to athletics. In particular, Engelen-van Melick et al demonstrated that the single leg hop is the most frequent measurement used to assess patients’ function more than two years after ACL reconstruction. Trigsted et al demonstrated less maximal knee flexion in the involved limb during the landing phase of a single leg hop in individuals who had returned to sport following ACL reconstruction compared to healthy controls. Xergia et al further demonstrated that individuals after ACL reconstruction landed with greater hip flexion on the involved limb compared to healthy controls. These studies highlight the continued asymmetries that exist in athletes after ACL reconstruction despite these individuals having returned to sport.

A recent systematic review demonstrated that knee extensor and flexor weakness along with hip extensor weakness is typical following ACL reconstruction and may persist for two years or more. Knee extensor and flexor strength deficits were associated with graft choice, indicating that extensor weakness is more common with patellar tendon grafts, while knee flexor weakness is associated with hamstring grafts. These altered biomechanics in landing when compared to the uninvolved limb can be directly attributed to these weaknesses. For example, Oberlander et al revealed that 78% of the extensor knee joint moment variability during the landing phase of a single leg hop at 12 months following ACL reconstruction was explained by the strength of the knee extensors. It remains unknown if hip extensor weakness would result in similar compensatory patterns in individuals post ACL reconstruction when performing dynamic landing activities, such as a single leg hop.

Therefore, the primary purpose of this study was to determine if relationships exist between hip extensors (primarily gluteus maximus) and maximum hip flexion and/or abduction/adduction during the landing phase of a single leg hop in both the involved and uninvolved limb of recreational athletes post ACL reconstruction and also in healthy controls. A secondary purpose was to determine if relationships exist between hip abductors and maximum hip flexion.
flexion and/or abduction/adduction as well. It was hypothesized that both groups would both exhibit significant associations between hip strength and hip kinematics during the landing phase of a single leg hop.

**METHODS**

**Participants and Screening**

Recreational athletes from 18 to 30 years old who had undergone unilateral ACL reconstruction, completed formal rehabilitation, and released by their physician to return to sport or activity were recruited via university email. A secondary group of healthy, recreational athletes was recruited from a population of convenience from the physical therapy program and matched to participants in the ACL group based on gender and activity level. Additional inclusion criteria required that participants in both groups were currently active in a sport or recreational activity a minimum of 2x/week for at least 30 minutes and participated in a jumping or cutting activity at least 1x/month. Participants in the ACL reconstruction group were excluded if they had any other knee ligament injury requiring surgical repair. Participants were excluded from the healthy, recreational athlete group if they had scoliosis, limb length inequality, or history of low back pain or lower extremity injury in the prior six months that limited activity for more than two weeks.

All procedures were approved by the Institutional Review Board at the University of Tennessee at Chattanooga and all participants provided written informed consent to participate. All participants who met the inclusion criteria were screened for the presence of a limb length inequality or scoliosis. Participants were instructed to wear athletic shoes, shorts, and a t-shirt for the screening. Limb length inequality was assessed using an indirect method, while scoliosis was assessed using the forward bend test by a licensed physical therapist with 16 years of experience in outpatient orthopaedics. Any participant with a limb length inequality > 6.4 mm or having a positive forward bend test was excluded as both limb length inequality and scoliosis have the potential to affect hip posture and hip kinematics.

Participants’ height and weight were measured using a standard scale. The single leg hop for distance was also assessed for each limb, averaging three successful attempts. Participants were allowed free movement of their upper extremities during this single leg hop. Any participant who was unable to jump a distance of at least 75% of their height was excluded. This standardized distance requirement was adopted because participants were required to place their hands on their hips when performing the single leg hop during motion analysis. This requirement was based on the methods of Oberlander et al and helps control for the possibility of asymmetrical arm movement patterns that might occur due to hip weakness, particularly in the frontal plane. Controlling upper extremity movement was necessary because the upper extremities were not included in the biomechanical model used during motion analysis. Participants were then scheduled for their motion lab visit for a motion analysis of the landing phase of a single leg hop.

**Motion Analysis**

An 8-camera motion capture system (Vicon Motion Systems, Centennial, CO) sampling at 240 Hz was synchronized with two force platforms (Bertec Corporation, Columbus, OH) sampling at 960 Hz, to collect three-dimensional kinematics and ground reaction force data, respectively. Retroreflective markers were attached to both lower extremities and the pelvis and trunk prior to data collection. Markers placed over anatomical landmarks were used to define joint centers and segment coordinate systems (iliac crests, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, first and fifth metatarsal heads). Molded thermoplastic shells with four non-collinear markers were attached to pelvis, thigh and shank segments using neoprene wraps and Velcro. Three non-collinear markers were attached to the heel to assess rear-foot motion. A standing trial was collected and anatomical markers were removed.

Participants warmed up for five minutes by walking on a treadmill at a self-selected pace. Participants then stretched their quadriceps, hamstrings, and triceps surae for three repetitions of 30 seconds each. The single leg hop required each participant...
were instructed to give maximal effort, and verbal encouragement was given to elicit optimal contraction during each trial. Each contraction was held for five seconds, with a 30 second rest given between each trial. If a participant achieved a significantly higher score on the third trial, then two to three additional trials were performed to allow the participant to demonstrate maximal strength. The highest three trials were averaged for use in data analysis.

Data Reduction
Marker trajectories data were low-pass filtered using a fourth-order recursive Butterworth filter with cutoff frequencies of 8 Hz. Kinematic data were calculated using standard rigid body analysis techniques with Visual 3D software (C-Motion, Rockville, MD). Joint angles were determined using the joint coordinate system. Joint angles were defined using the right-hand rule with flexion-extension, abduction-adduction, and internal-external rotation as the first, second, and third rotation, respectively. The landing phase, defined as the period from initial foot contact (ie, > 10N) to peak knee flexion angle, was of interest. Peak values for hip flexion and abduction/adduction angles that occurred during the landing phase were determined for each trial and averaged. Strength measures for each participant were normalized to the participant’s height and weight.

Statistical Analysis
Descriptive statistics were calculated for demographic variables and single leg hop test data. Independent t-tests were used to analyze any potential differences between groups related to demographic measures and the single leg hop test. Absolute limb symmetry indexes were also calculated for both groups for the single leg hop test during the screening process. The absolute limb symmetry index (LSI) was calculated by dividing the smaller average hop distance of either limb by the larger average hop distance of the other limb and multiplying by 100%. The absolute LSI allows for between group comparisons since limbs may differ based on surgical status or limb dominance. All dependent variables were assessed for normality using the Shapiro-Wilk test. Dependent and independent t-tests were used to analyze any potential differences in maximum hip flexion and hip abduction/adduction angles and hip
extensor and abductor strength within and between groups, respectively. The limb that underwent ACL reconstruction was the limb of interest in the ACL group for between group comparisons. The limb used for statistical comparison in the healthy group was the right limb based on the fact that there were no limb differences in hop distance or hip kinematics for the healthy participants. Furthermore, all healthy participants reported their right limb as being dominant (ie, the leg used to kick a ball for maximum distance). A LSI for hip extensor and abductor strength values was also calculated for the ACL group by dividing the average strength value of the involved limb by the average strength value of the uninjured limb and multiplying by 100%. Scatterplots were assessed prior to calculation of the Pearson correlation coefficient ($r$) to assess for the presence of a linear relationship and possible outliers. Pearson’s $r$ was used to assess for any potential relationships between hip strength and hip kinematics in the limbs of interest in both groups. Pearson’s $r$ was interpreted as follows: $>.75-1.0 = \text{good to excellent}; .50-.75 = \text{moderate}; .25-.50 = \text{fair};$ and $0.00-.25 = \text{little or no relationship}$. A $P < .05$ was utilized for all statistical analyses.

**RESULTS**

A total of 24 participants (12 ACL/12 healthy) met the inclusion criteria and completed the study protocol. Each group consisted of seven females and five males. Only one potential ACL participant was unable to achieve the required hop distance of 75% of their height and was not allowed to continue in the study. The healthy control group was slightly older than the ACL reconstruction group, while other demographic data and single leg hop values were similar (Table 1). The participants in the ACL group had undergone surgery an average of 32 months (range 9-58) prior to study participation. Seventy-five percent of participants in the ACL group suffered non-contact injuries, with the remaining injuries occurring via contact. Seven of the injuries occurred to the right knee and five to the left knee. The majority of participants had their ACL reconstructed using an autograft (11/12) with the vast majority of these grafts being patella tendon (10/11) and the other being hamstring tendon (1/11). The remaining participant’s ACL was repaired with an allograft tendon. Half of the ACL participants reported a known meniscal injury as well.

**Strength and Kinematic Variables Within ACL Group**

All dependent variables of interest met the assumption of normality. No significant differences were noted between limbs for peak hip flexion and abduction/adduction angles during the landing phase of a single leg hop (Table 2). Likewise, no significant differences were noted between limbs for hip extensor or abductor strength (Table 2). The limb symmetry index for the hip extensors was $93% \pm 15$ and $105% \pm 08$ for the hip abductors.

**Strength and Kinematic Variables Between Groups**

An independent t-test revealed that the hip extensor strength of the ACL group was statistically

### Table 1. Mean (SD) of demographic variables for participants in both groups.

<table>
<thead>
<tr>
<th></th>
<th>ACL Group</th>
<th>Healthy Control</th>
<th>p-value (t-value, df)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>20.8 (2.1)</td>
<td>23.9 (1.4)</td>
<td>&lt;.001* (-4.27, 22)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.68 (0.08)</td>
<td>1.72 (0.08)</td>
<td>.20 (-1.34, 22)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.1 (6.7)</td>
<td>69.6 (11.5)</td>
<td>.88 (0.15, 22)</td>
</tr>
<tr>
<td>Single leg hop distance (cm)</td>
<td>167.7 (3.9)</td>
<td>159.7 (3.0)</td>
<td>.52 (0.65, 22)</td>
</tr>
<tr>
<td>Absolute LSI (%)</td>
<td>94.0 (3.9)</td>
<td>95.9 (3.1)</td>
<td>.19 (-1.36, 22)</td>
</tr>
</tbody>
</table>

ACL= anterior cruciate ligament, df= degrees of freedom, LSI= limb symmetry index. *$p<.05$.

### Table 2. Mean (SD) of kinematic and strength variables for involved and uninjured limbs in the ACL group.

<table>
<thead>
<tr>
<th></th>
<th>Involved Limb</th>
<th>Uninvolved Limb</th>
<th>p-value (t-value, df)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip extensor strength (N/Hz*BW)</td>
<td>0.18 (0.05)</td>
<td>0.19 (0.07)</td>
<td>.77 (-0.27, 22)</td>
</tr>
<tr>
<td>Hip abductor strength (N/Hz*BW)</td>
<td>0.30 (0.08)</td>
<td>0.28 (0.06)</td>
<td>.63 (0.54, 22)</td>
</tr>
<tr>
<td>Maximum hip flexion angle (°)</td>
<td>43.0 (3.4)</td>
<td>45.6 (2.8)</td>
<td>.54 (-0.62, 22)</td>
</tr>
<tr>
<td>Maximum hip abduction/adduction angle (°)</td>
<td>9.0 (3.2)</td>
<td>6.4 (3.4)</td>
<td>.32 (1.03, 22)</td>
</tr>
</tbody>
</table>

ACL= anterior cruciate ligament, df= degrees of freedom, N= newton, Hz= height, BW=body weight.
Hip Strength and Kinematic Associations in the Healthy Group

A fair and non-significant relationship was demonstrated for hip abductor strength and hip flexion angle ($r = 0.39$, $p = 0.21$). Little to no associations were demonstrated between hip extension strength and hip flexion angle ($r = 0.09$, $p = 0.79$), hip extension strength and hip abduction/adduction angle ($r = 0.15$, $p = 0.65$), or hip abductor strength and hip abduction/adduction angle ($r = -0.17$, $p = 0.60$).

DISCUSSION

The purpose of this study was to analyze potential relationships between hip strength and hip kinematics during the landing phase of a single leg hop in individuals post ACL reconstruction and a healthy group of recreational athletes. It was hypothesized that both groups would exhibit significant associations between maximal isometric hip strength and peak hip kinematics during the landing phase of a single leg hop. This hypothesis was only partially supported by the fact that moderate associations were demonstrated in the ACL group, but not in the healthy recreational athletes. Specifically, a moderate and indirect relationship was present between the hip extensors and maximum hip abduction/adduction angle, while a moderate and direct relationship existed for the hip abductors and maximum hip flexion angle.

The most interesting finding was the indirect relationship between the hip extensors and maximum hip abduction/adduction angle during the single leg hop. This relationship suggests that individuals after ACL reconstruction who have relatively strong hip extensors land with less dynamic knee valgus compared to those with weak hip extensors (see Table 1). Powers has recently suggested that the gluteus maximus is capable of producing hip abduction. Fujisawa et al demonstrated that the gluteus maximus was active during isometric hip abduction and the activity increased as the hip flexion angle increased. A recent study by Cronin et al supports the notion that the hip extensors play a key role in minimizing frontal plane hip motion during the landing phase of a single leg hop followed by a cutting
phase of a single leg hop as opposed to controlling hip adduction. This suggestion is based on the direct relationship seen between hip abductor strength and the maximum hip flexion angle. It might be the case that a person with strong hip abductors is able to maintain a more level pelvis thus enabling greater hip flexion to occur during the landing. Pollard et al.\textsuperscript{48} demonstrated that adolescent female soccer players that exhibited high amounts of hip and knee flexion during a drop landing task also exhibited decreased internal knee adductor moments. Therefore, increased hip flexion may also lead to less frontal plane loading at the knee joint.

Landing kinematics demonstrated that individuals post ACL reconstruction land with greater peak hip adduction angles compared to those individuals in the healthy group. The increased knee adduction differs from Trigsted et al.\textsuperscript{28} who saw similar peak hip adduction patterns during a single leg hop landing between participants who had undergone ACL reconstruction compared to healthy controls. A difference in methodology may explain these differences.

Figure 1. (a) representative landing of a participant with “strong” hip extensors and (b) representative landing of a participant with “weak” hip extensors. Note: Images sampled at maximum knee flexion.
differences as Trigsted et al\textsuperscript{28} had their participants hop for maximum distance. Increased hip adduction is an undesired movement pattern during a jump landing due to the decreased ability to avoid dynamic valgus collapse. Furthermore, the results demonstrated that peak hip flexion and adduction were similar between limbs in the ACL group. These results differ from those of Trigsted et al\textsuperscript{28} who reported less peak hip flexion in the involved limb while peak hip adduction angles were similar. Again, this lack of agreement could be explained by differences in methodology. Typically, symmetry between limbs is a desired outcome. However, the fact that the ACL group landed with greater hip adduction compared to the healthy control group is of concern for the overall limb alignment as it relates to a potential increase in dynamic knee valgus.

The ACL group exhibited significant weakness in their hip extensors, which may partially explain the increased hip adduction seen during the jump landing. It should be noted that quadriceps weakness common seen after ACL reconstruction\textsuperscript{30} is also another potential cause linked to the kinematic asymmetries. Recent studies have demonstrated the significant effects of weak quadriceps on landing mechanics\textsuperscript{49} and bilateral hip extensor strength\textsuperscript{50} for individuals who had a previous ACL reconstruction. Future studies, therefore, should attempt to perform strength measurements of all major lower extremity muscle groups in addition to measurements of trunk/core stability. In addition, body marker sets that include not only the pelvis and lower extremities, but also the trunk and upper extremities should be included in the methods to help researchers determine the influence of strength deficits on whole body movement patterns.

The other important finding is that significant associations between hip strength and hip kinematics exist in the ACL group, but not in the healthy comparison group. We are unaware of any other study that has demonstrated an association between strength and kinematics in a group of individuals post ACL reconstruction, but not present in the healthy comparison group. It could be speculated that movement strategies related to single leg jump landings likely differ in the presence of weakness. ACL reconstruction rehabilitation guidelines frequently suggest introducing single leg landing activities as early as three to four months post-surgery.\textsuperscript{51,52} Therefore, individuals three to four months post ACL reconstruction likely exhibit limited variability in movement patterns during a jump landing due to lower extremity strength deficits, especially in the sagittal plane. Limited variability in movement has been suggested as a cause of injury and is therefore an undesired trait.\textsuperscript{53} Limited hip strength may result in a reduced number of movement patterns and might explain why participants in the ACL group demonstrated significant associations with hip strength compared to healthy individuals. Individuals with hip weakness may rely more on ligament dominance.\textsuperscript{54} Limited variability may also be linked to the risk of subsequent ACL injury. The results suggest that the ACL group on average had an acceptable LSI of 90% for their hip extensors. However, both limbs in the ACL group could be considered weaker when compared to the healthy control group. This finding alone highlights the importance of an increased focus on development of hip extensor strength in individuals after ACL reconstruction.

Overall, the results of this study suggest that researchers and clinicians should focus more on the function of the hip extensors, in particular the gluteus maximus, in efforts to improve lower extremity kinematics observed during sporting activities. A recent evidence-based review has highlighted the value of hip-specific neuromuscular exercise interventions that are capable of modifying dynamic knee valgus in efforts to prevent anterior cruciate ligament (ACL) injuries.\textsuperscript{12} Recent work by Stearns and Powers\textsuperscript{55} demonstrated that following a four-week training program which increased hip extensor and abductor strength, healthy female recreational athletes demonstrated improved landing mechanics during a drop-jump task. It remains unknown whether a similar training program would also produce improvements in landing mechanics during dynamic tasks, such as a single leg hop in individuals after ACL reconstruction.

Limitations
This study contains some limitations. First, even though the sample is representative of the general population who typically incur ACL injuries, the sample size remains relatively small. Secondly, the
sample was selected based on convenience and further limited to college-age, recreational athletes whose ACL reconstruction occurred approximately 32 months prior. Specific information related to self-reported function was not collected, but we feel that the ACL group was comparable to participants in other cross-sectional studies. Nyland et al demonstrated that individuals who thought they were capable of participating in their current sport activities had an IKDC score of 87.2 on average. Trigsted et al reported a similar average IKDC score of 88.6 for females following ACL reconstruction that were of similar age and activity level compared to participants in the ACL group. Furthermore, single leg hop distance of the females in their study was similar to the hop distance of the females who participated in this study. Therefore, we feel that the ACL group who participated in this study would have similar IKDC scores when compared to participants in both of these studies. The majority of participants in this study had also undergone ACL reconstruction utilizing a bone-tendon-bone graft. Thus, these results cannot be applied to individuals who had their ACL reconstructed with other graft sources (ie, hamstring tendon or allograft). The study design also did not allow for a uniform postoperative rehabilitation process. However, all participants did report having undergone formal physical therapy after surgery. Additionally, the influence of trunk position on lower extremity biomechanics was not assessed during a landing from a single leg hop and should not be discounted. Oberlander et al demonstrated that individuals who have undergone ACL reconstruction tend to demonstrate greater forward and ipsilateral trunk lean during single leg hop landings. The results of this study apply specifically to the performance of a single leg hop test, as other movements were not investigated. Finally, this study does not explain all of the variation in hip kinematics during the landing of a single leg hop. Other factors that affect landing kinematics should be studied.

CONCLUSIONS

College-aged recreational athletes who were on average 32 months removed from ACL reconstruction had decreased hip extensor strength and landed with greater hip adduction compared to healthy controls. Significant associations were demonstrated between hip strength and hip kinematics, but only for participants in the ACL group. The results suggest that hip extensors, particularly the gluteus maximus, may serve to contribute to hip adduction, while the hip abductors may play more of a role in stabilizing the pelvis in space and may contribute to the amount of hip flexion that occurs during a single leg hop landing. Researchers and clinicians alike should consider the importance of the hip extensors in playing an important role in controlling frontal plane motion of the hip following ACL reconstruction.

REFERENCES


ABSTRACT

Background/Purposes: Prospective studies utilizing standardized injury and exposure measures are needed to consolidate our knowledge of injury incidence and associated risk factors for musculoskeletal injury amongst pre-professional dancers. The purpose of this study was to investigate the injury incidence amongst pre-professional dancers attending a fulltime training school in New Zealand. The secondary purposes of this study were to investigate the relationship between dance exposure and injury risk, and the relationship between risk factors (specifically the MCS outcome scores) and injury risk.

Methods: A prospective cohort study of 66 full-time pre-professional dancers was undertaken over one full academic year (38 weeks), included 40 females (mean age 17.78 yrs, SD 1.18) and 26 males (mean age 18.57yrs, SD 1.72). Injury surveillance included both reported and self reported injury data. Dancers were screened using the MCS in the first week of term one.

Results: Eighty-six per cent of dancers sustained one or more injuries. Fifty-nine per cent of all injuries were time-loss. The injury incidence rate was 2.27 per 1000 hours of dance exposure (DEhr) and 3.35 per 1000 dance exposures (DE). There was a significant association between the total number of injuries and total DE per month (B=0.003, 95% CI 0.001 - 0.006, p=0.016). Dancers who had a MCS score < 23 were more likely to be injured than those who scored ≥23 (B= -0.702, 95% CI = -1.354 – -0.050, p=0.035).

Conclusion: Injury prevalence and incidence was comparable with other international cohorts. The number of dance exposures was more highly associated with injury risk than the hours of dance exposure. The MCS may be a useful tool to help identify dancers at risk of injury.

Level of Evidence: Level 3b, Prospective Longitudinal Cohort Study

Keywords: Dance, exposure, functional movement screening, injury, pre-professional

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INTRODUCTION

Pre-professional dance training is demanding, and requires significant physical and artistic ability.1,2 Long training hours coupled with highly repetitive movement patterns during a time of maturation and development places the pre-professional dancer in a vulnerable position with regard to injury risk.3,4 Several authors have highlighted musculoskeletal injuries as a significant ongoing health issue for pre-professional dancers.1,3,5-20 However, consistent reporting of injury incidence is still necessary to enable the development and monitoring of injury prevention strategies.1,21-23

Risk factors for dance related injury are still not well understood.1,5,6,24 The negative effects of changes in training load and/or training loads beyond an athlete’s capacity have been cited as potential risk factors for injury.25-31 To date there is a paucity of prospective studies examining the relationship between dance exposure and injury risk amongst pre-professional dancers.1,12,16,32,33

Pre-participation or pre-season screening within dance schools and professional companies has become more widely adopted as the need to optimize dancers’ health is recognized as a critical factor in both developing and maintaining talent.34-42 Functional movement screening tools designed to identify deficits in neuromuscular control, have gained popularity within the sporting arena as an effective and efficient screening strategy.43-50 The utility of functional movement screening tools, and more specifically the MCS, to detect dancers at risk of injury requires further investigation.45,47,51,52

The purpose of this study was to investigate the injury incidence amongst pre-professional dancers attending a fulltime training school in New Zealand. The secondary purposes of this study were to investigate the relationship between dance exposure and injury risk amongst pre-professional dancers.3,12,16,32,33,53

METHODS

Study design

A prospective cohort study was conducted over one full academic year (38 weeks). Approval for was gained from the Auckland University of Technology (AUT) Ethics Committee. All participants received both verbal and written study information and gave written informed consent.

Participants

Students attending an elite full-time pre-professional dance school in New Zealand were invited to participate (n=86). A total of 66 dancers completed the necessary documentation and movement screening session at the beginning of the study.

Injury Surveillance

Participating dancers completed an initial questionnaire that collected information on potential risk factors including: age, height, weight, BMI, gender, previous and current injury history, year of pre-professional dance training, dance major, and age started dancing. Prospective injury surveillance was undertaken over one full academic year. The dance school physiotherapist completed a standardized Injury Summary Sheet (Appendix 1) and International Performing Arts Injury Reporting Survey (IPAIRS©) for all reported injuries. Self-reported injury data was collected via an online survey tool (http://surveymonkey.com) and sent to participating students every three weeks. Injury was defined as, “any physical complaint sustained by a dancer resulting from performance, rehearsal or class, and resulting in a dancer injury report or triage, irrespective of the need for medical attention or time-loss from dance activities”.53 Injury was then also sub-classified based on current recommendations; including time-loss or non time-loss, nature of injury i.e. acute or overuse, and if an injury was new or recurrent.54-56 Recurrent injuries were further classified as exacerbations or re-injuries.55 (Appendix 2) Injury severity was coded, S0 (no days off or modified), S1 (activity modification), S2 (≤ 7 days off), S3 (> 7 days off) or S4 (year ending).3,57

Dance Exposure

Dance exposure (DE) was defined as, “one dancer participating in one class, rehearsal or performance in which he or she is exposed to the possibility of dance injury regardless of the time associated with that participation”.58 Total dance exposure (hours and events), was calculated from the weekly timetables for each year of study (major and gender).

MCS screening and scoring

All participants were screened using the Movement Competency Screen (MCS©) in the first week of term
The MCS is comprised of five fundamental movement patterns (body weight squat, lunge twist, single leg squat, bend and pull, push up) and three dynamic jump patterns (counter movement jump, counter movement jump with unilateral land, broad jump with unilateral land) (Appendix 3, Appendix 4). The subjects were filmed using Casio EX-ZR100 digital cameras (Shibuya-ku, Tokyo). Video analysis of each movement pattern was performed by the primary researcher, and scored using standardized criteria directly adapted from the original MCS 100 criteria described by Kritz, and that were used by Vanweerd for the Netball Movement Competency Screen. Whole body movement is assessed for each movement pattern and scored from 0 – 3, based on identification of primary or secondary areas of concern as described by Kritz. Primary areas of concern are those that are most likely to impact on the athlete’s movement competency during the selected movement task. A score of one indicates poor movement competency, while a score of three indicates good movement competency. All unilateral movements were assessed and scored bilaterally. The scores of all individual movements were totalled to provide a composite outcome score (out of a possible 36). The reliability of the MCS has been shown to be good to excellent in adolescent female netballers and in military populations. Prior to the current study a pilot study assessed the intra-rater reliability of the primary researcher using the MCS. Intra-rater reliability was established using average measures intra-class correlation coefficient (ICC). The ICC for the overall MCS scores in ten subjects was excellent (ICC 0.99, CI 0.98 - 0.99).

**Statistical Analysis**

Descriptive analysis of the data established the injury prevalence and incidence of reported injuries. Injury prevalence was defined as the total number of reported injuries in one full academic year. Injury incidence over the academic year (Jan-Dec) was expressed as the number of reported injuries per 1000 hours of dance exposure (DEhr). Injury rates were also calculated using the number of reported injuries per 1000 dance exposures (DE), as it is considered to achieve a higher level of reliability as well as comparability between cohorts, and is also consistent with reporting methods utilized by other international sporting bodies. Pearson’s correlations were used to determine the relationship between dance exposure and injury. A univariate linear regression model was used to investigate the relationship between injury status and individual potential risk factors. A multivariate linear regression model was used to examine the influence of a combination of risk factors for becoming injured. Covariates were fitted into the model using a forward selection procedure and were retained in the final linear regression model if they reached a statistical threshold of p<0.10 or were of clinical significance. A logistic regression was used to investigate the relationship between injury severity and possible risk factors. All analyses were performed using Statistical Programme for Social Science (SPSS) software (SPSS V.22, IBM Corporation, New York, USA). Alpha levels were set at 0.05 (95% confidence level).

**RESULTS**

**Participants**

Sixty-six dancers (females = 40, males = 26) aged between 16-24 years old (mean 18.15yrs, SD 1.45) gave consent to participate. There were 28 dancers in year one, 25 in year two and 13 in year three. Thirty-two were ballet majors and 34 were modern majors. Seventy-seven per cent of dancers attending the dance school participated in the study. During the course of the study one dancer opted out of reported injury data collection and four dancers left the school. Demographic characteristics of participants are presented in Table 1.

**Injury Prevalence**

Fifty-seven (86.4%) dancers reported a history of previous dance related injury at the start of the study. A total of 125 reported injuries, involving 56 dancers (86.2%), were recorded over the academic year. Injury prevalence across the year ranged from 1.5% to 36.9% per month. No significant demographic differences were found between dancers who reported any injury or time-loss injuries and those who did not (Table 2).

**Injury Characteristics**

Reported injury characteristics are shown in Table 3. The ankle was the most common site of lower limb injury, followed by the knee, foot, and hip/thigh respectively. The thoracic spine was the most
common site of trunk injury, followed by the lumbar spine. The shoulder was the most common upper limb injury.

**Injury Severity**

Of all reported injuries, 59.2% (n = 74) were time-loss resulting in a total of 433 full days off dance. Eighty-six per cent (n = 64) of all time-loss injuries required the dancer to take ≤ 7 days off dance (S2), with 13.5% (n = 10) taking >7 days off dance (S3). Injuries requiring the greatest time off dance included: lower limb stress fractures, posterior cruciate and meniscal injury, and tendon injuries of the foot and ankle. The distribution of injury severity via injury location is presented in Figure 1.

**Injury Incidence**

The total injury incidence rate over the academic year was 2.27 (95% CI 2.25-2.28) per 1000 dance exposure hours (DEhr) and 3.35 (95% CI 3.33-3.37)

<table>
<thead>
<tr>
<th>Table 1. Demographic data, reported as mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Sample</td>
</tr>
<tr>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Subjects (n)</td>
</tr>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>(range: 16 - 24)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>(range: 16 - 24)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>BMI</td>
</tr>
<tr>
<td>Age started dancing (yrs)</td>
</tr>
</tbody>
</table>

BMI= Body mass index
*Statistically significant at p<0.05

<table>
<thead>
<tr>
<th>Table 2. Descriptive characteristics of injured and non-injured groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury reported</td>
</tr>
<tr>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>BMI</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Injuries reported</th>
<th>Injury reported (%)</th>
<th>No injury reported (%)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>49 (87.5%)</td>
<td>8 (88%)</td>
<td>0.600†</td>
</tr>
<tr>
<td>Previous history injury</td>
<td>49 (87.5%)</td>
<td>8 (88%)</td>
<td>0.600†</td>
</tr>
<tr>
<td>Current injury</td>
<td>10 (17.9%)</td>
<td>1 (12%)</td>
<td>1.000†</td>
</tr>
<tr>
<td>Gender Male</td>
<td>22 (39.3%)</td>
<td>3 (33.3%)</td>
<td>1.000†</td>
</tr>
<tr>
<td>Female</td>
<td>34 (60.7%)</td>
<td>6 (66.6%)</td>
<td>1.000†</td>
</tr>
<tr>
<td>Major Ballet</td>
<td>27 (48.2%)</td>
<td>5 (55.6%)</td>
<td>1.000†</td>
</tr>
<tr>
<td>Modern</td>
<td>29 (51.8%)</td>
<td>4 (44.4%)</td>
<td>1.000†</td>
</tr>
<tr>
<td>Year of training 1st</td>
<td>23 (41.1%)</td>
<td>4 (44.4%)</td>
<td>0.902†</td>
</tr>
<tr>
<td>2nd</td>
<td>21 (37.5%)</td>
<td>4 (44.4%)</td>
<td>1.000†</td>
</tr>
<tr>
<td>3rd</td>
<td>12 (21.4%)</td>
<td>1 (11.1%)</td>
<td>1.000†</td>
</tr>
</tbody>
</table>

N= number of dancers; SD = standard deviation; BMI= Body mass index
† p-value calculated using fishers exact test
The total injury incidence for time-loss injuries was 1.34/1000DEhr and 1.98/1000DE’s. The injury incidence rates, for reported injuries were similar for males and females (2.39 and 2.19/1000DEhr), and ballet and modern dancers (2.11 and 2.17/1000DEhr). First year students had the highest injury incidence rate for reported injuries (2.95/1000DEhr). Injury incidence also decreased term-by-term, with the highest incidence in term one (3.60/1000DEhr). Injury incidence (DEhr and DE) for reported injuries is presented in Table 4 and 5.

Relationship between dance exposure and injury
The total number of dance exposures (DE) per month was significantly associated with the total number of reported injuries reported per month (p=0.016) (Figure 2). A significant association was also found between the average number of dance exposures (DE) per dancer per month and the total number of injuries per month (p=0.027). The total hours of dance exposure (DEhr) was found not to be a significant predictor of injury (p=0.964).

Table 3. Characteristics and severity of reported and self-reported injuries

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Reported Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
</tr>
<tr>
<td>Total injuries</td>
<td>125</td>
</tr>
<tr>
<td>% dancers injured</td>
<td></td>
</tr>
<tr>
<td>New</td>
<td>104</td>
</tr>
<tr>
<td>Recurrent</td>
<td>21</td>
</tr>
<tr>
<td>- Re injury</td>
<td>8</td>
</tr>
<tr>
<td>- Exacerbation</td>
<td>13</td>
</tr>
<tr>
<td>Acute</td>
<td>51</td>
</tr>
<tr>
<td>Overuse</td>
<td>74</td>
</tr>
<tr>
<td>Head/Neck</td>
<td>4</td>
</tr>
<tr>
<td>Trunk</td>
<td>25</td>
</tr>
<tr>
<td>Lower Limb</td>
<td>85</td>
</tr>
<tr>
<td>Upper Limb</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injury Severity</th>
<th>Reported as mean (SD) or n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean numerical pain score</td>
<td>5.29 (1.91)</td>
<td></td>
</tr>
<tr>
<td>Time-loss injuries:</td>
<td>n=74</td>
<td>59.2</td>
</tr>
<tr>
<td>Full days off dance</td>
<td>5.85 (6.37) (range: 1 - 42 days)</td>
<td></td>
</tr>
<tr>
<td>Non time-loss injuries:</td>
<td>n= 51</td>
<td>40.8</td>
</tr>
<tr>
<td>Days of modified activity</td>
<td>7.14 (5.49) (range: 0 - 28 days)</td>
<td></td>
</tr>
<tr>
<td>Activity modification:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>none</td>
<td>n=1</td>
<td>2</td>
</tr>
<tr>
<td>mild</td>
<td>n=7</td>
<td>14</td>
</tr>
<tr>
<td>moderate</td>
<td>n=43</td>
<td>84</td>
</tr>
<tr>
<td>severe</td>
<td>n=0</td>
<td>0</td>
</tr>
</tbody>
</table>

SD = standard deviation n = number

per 1000 dance exposures (DE). The injury incidence for time-loss injuries was 1.34/1000DEhr and 1.98/1000DE’s. The injury incidence rates, for reported injuries were similar for males and females (2.39 and 2.19/1000DEhr), and ballet and modern dancers (2.11 and 2.17/1000DEhr). First year students had the highest injury incidence rate for reported injuries (2.95/1000DEhr). Injury incidence also decreased term-by-term, with the highest incidence in term one (3.60/1000DEhr). Injury incidence (DEhr and DE) for reported injuries is presented in Tables 4 and 5.

Relationship between reported injuries and risk factors
The association between potential risk factors and injury is presented in Table 6. A MCS score <23 was significantly associated with increased risk of injury (p=0.035). Furthermore, the higher number of injuries in those with a MCS score <23 was more likely to be explained by a greater number of trunk injuries (p=0.036). No significant difference in total MCS scores was found for age, gender, major, or year group (p>0.05).
A history of previous injury was found not to be associated with increased injury risk. However, a significant association between previous history of injury and gender was noted, whereby more females had sustained previous injuries compared to males \((p=0.022)\). A significant association was found between injury location and major, whereby modern majors were more likely than ballet majors to sustain trunk injuries \((B=-0.304, p=0.042)\) and upper limb injuries \((B=0.324, p=0.001)\). Upper limb injuries were more common amongst first year students, decreasing for every year of study \((B=-0.152, p=0.025)\).

DISCUSSION

Participants

The key strengths of this prospective study included: (1) seventy-seven per cent of eligible dancers participated in the study, (2) the use of reported injury and exposure data collected over a full academic year and, (3) this is the first prospective longitudinal study of elite pre-professional dancers in New Zealand.

Prevalence, incidence and severity

Prevalence

At the start of the study 86\% \((n=57)\) of dancers reported a previous history of dance-related injury. This was comparable with previous studies \((82-95\%)\). The injury prevalence over the academic year was \((86.2\%)\), which was within the upper range reported in current literature \((30-94\%)\). Further to this, 21\% of injuries sustained were considered ‘recurrent’, 8\% of which were re-injuries. This was fewer than that reported by Ekegren, Quested, Brodrick where 14\% of time-loss injuries were considered a re-injury. Future research utilizing the Subsequent Injury Categorization (SIC) model as proposed by Finch and Marshall may enable a better understanding between injury and each subsequent injury; which can have a considerable impact on a dancer’s training and career.

Table 4. Injury incidence rates for reported injuries per dance exposure hours (DEhr)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Subjects</th>
<th>Total Injuries RI</th>
<th>Total DEhr</th>
<th>Mean DEhr</th>
<th>SD</th>
<th>95% CI</th>
<th>Reported Injuries per 1000 DEhr</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>27</td>
<td>41.5</td>
<td>69</td>
<td>741:30</td>
<td>180:00</td>
<td>670:16 – 812:43</td>
<td>2.95</td>
<td>2.92 – 2.97</td>
</tr>
<tr>
<td>Year 2</td>
<td>25</td>
<td>38.5</td>
<td>54</td>
<td>909:19</td>
<td>148:22</td>
<td>848:04 – 970:33</td>
<td>1.94</td>
<td>1.92 – 1.95</td>
</tr>
<tr>
<td>Year 3</td>
<td>13</td>
<td>20.0</td>
<td>32</td>
<td>954:26</td>
<td>86:58</td>
<td>901:52 – 1006:59</td>
<td>1.77</td>
<td>1.75 – 1.79</td>
</tr>
<tr>
<td>Female</td>
<td>40</td>
<td>61.5</td>
<td>162</td>
<td>855:46</td>
<td>158:34</td>
<td>805:46 – 906:29</td>
<td>2.19</td>
<td>2.18 – 2.21</td>
</tr>
<tr>
<td>Ballet</td>
<td>31</td>
<td>47.7</td>
<td>24</td>
<td>854:40</td>
<td>217:03</td>
<td>705:03 – 846:17</td>
<td>2.11</td>
<td>2.10 – 2.13</td>
</tr>
<tr>
<td>Modern</td>
<td>34</td>
<td>52.3</td>
<td>123</td>
<td>906:57</td>
<td>103:32</td>
<td>870:44 – 943:04</td>
<td>2.17</td>
<td>2.16 – 2.19</td>
</tr>
<tr>
<td>Time-Loss</td>
<td>43</td>
<td>66.1</td>
<td>144</td>
<td>848:33</td>
<td>177:12</td>
<td>804:43 – 892:32</td>
<td>1.34</td>
<td>1.33 – 1.35</td>
</tr>
<tr>
<td>Non Time-Loss</td>
<td>35</td>
<td>53.8</td>
<td>141</td>
<td>848:33</td>
<td>177:12</td>
<td>804:43 – 892:32</td>
<td>0.92</td>
<td>0.91 – 0.93</td>
</tr>
<tr>
<td>Total Cohort</td>
<td>65</td>
<td>100.0</td>
<td>650</td>
<td>848:33</td>
<td>177:12</td>
<td>804:43 – 892:32</td>
<td>2.27</td>
<td>2.25 – 2.28</td>
</tr>
</tbody>
</table>

\(N=\) number of subjects  \(RI=\) reported injuries  \(DEhr=\) dance exposure hours  \(CI=\) confidence interval
Incidence

Prospective studies utilizing reported injury data and a mixed cohort with which to compare the overall results of this study are lacking. The incidence of reported injuries for ballet majors alone was 2.11/1000DEhr, which although comparable with previous studies, is at the upper end of the range (range: 0.9-2.9/1000hrs).11,16,18 Fewer studies have reported the injury incidence for modern dance students. In this study the injury incidence (2.17/1000) was somewhat lower than the 4/1000hours of dance reported amongst modern dancers at the Escuela Nacional de Danza in Mexico.13 Comparisons between dance schools should, however, be made with caution as differences in demands, nature of exposures, and age of dancers may also impact on injury rates.

Table 5. Injury incidence rates for reported injuries per number of dance exposures (DE)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Subjects</th>
<th>Total Injuries RI</th>
<th>Total DE</th>
<th>Mean DE</th>
<th>SD</th>
<th>95% CI</th>
<th>Reported Injuries per 1000 DE</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>27</td>
<td>41.5</td>
<td>59</td>
<td>13771</td>
<td>510.04</td>
<td>142.79</td>
<td>453.55 – 566.52</td>
<td>4.28</td>
</tr>
<tr>
<td>Year 2</td>
<td>25</td>
<td>38.5</td>
<td>44</td>
<td>15258</td>
<td>610.32</td>
<td>100.75</td>
<td>568.73 – 651.91</td>
<td>2.88</td>
</tr>
<tr>
<td>Year 3</td>
<td>13</td>
<td>20.0</td>
<td>22</td>
<td>8285</td>
<td>637.31</td>
<td>25.62</td>
<td>621.82 – 652.00</td>
<td>2.66</td>
</tr>
<tr>
<td>Male</td>
<td>25</td>
<td>38.5</td>
<td>50</td>
<td>14113</td>
<td>564.52</td>
<td>140.50</td>
<td>506.52 – 622.52</td>
<td>3.54</td>
</tr>
<tr>
<td>Female</td>
<td>40</td>
<td>61.5</td>
<td>75</td>
<td>23201</td>
<td>580.03</td>
<td>113.19</td>
<td>543.82 – 616.22</td>
<td>3.23</td>
</tr>
<tr>
<td>Ballet</td>
<td>31</td>
<td>47.7</td>
<td>58</td>
<td>17138</td>
<td>552.83</td>
<td>167.86</td>
<td>491.26 – 614.41</td>
<td>3.38</td>
</tr>
<tr>
<td>Modern</td>
<td>34</td>
<td>52.3</td>
<td>67</td>
<td>20176</td>
<td>593.41</td>
<td>56.43</td>
<td>573.72 – 613.10</td>
<td>3.32</td>
</tr>
<tr>
<td>Time-Loss</td>
<td>43</td>
<td>66.1</td>
<td>74</td>
<td>37314</td>
<td>574.06</td>
<td>123.57</td>
<td>543.44 – 604.68</td>
<td>1.98</td>
</tr>
<tr>
<td>Non Time-Loss</td>
<td>35</td>
<td>53.8</td>
<td>51</td>
<td>37314</td>
<td>574.06</td>
<td>123.57</td>
<td>543.44 – 604.68</td>
<td>1.37</td>
</tr>
<tr>
<td>Total Cohort</td>
<td>65</td>
<td>100.0</td>
<td>125</td>
<td>37314</td>
<td>574.06</td>
<td>123.57</td>
<td>543.44 – 604.68</td>
<td>3.35</td>
</tr>
</tbody>
</table>

N = number of subjects   RI= reported injuries   DE = dance exposures   CI = confidence interval

Figure 2. Dance exposure and injury.
The findings of this study support current evidence that overuse injuries are a significant issue for dancers.\(^2,7,11,16,17,66,67\) The incidence of overuse injuries was found to be lower than that reported in a recent study of pre-professional ballet dancers (2.4/10000DEhr and 3.52/1000DE).\(^3\) The shorter inception period of the compared study (6 months) and single genre cohort may contribute to these differences. Comparatively, Ekegren, Quested, Brodrick\(^7\) reported a higher prevalence of overuse injuries (72%) compared to this current study (59.2%). The higher average dance exposure per year (1030hr) may be a contributing factor, whereby longer training hours, with less relative time for recovery is considered a significant extrinsic risk factor for sustaining overuse injuries.\(^25,68\)

### Severity

Severity of injuries amongst pre-professional dancers has, thus far, been infrequently reported and the different measures utilized to define injury severity have also limited comparisons. The injury incidence for time-loss injuries in this study was comparable with findings from a recent prospective study of 266 pre-professional ballet dancers in London that utilised the same time-loss injury definition (1.38/10000DEhr, 1.87/1000DE).\(^7\) The current study found the majority of injuries to be classified as S2 (≤7 days off dance). Although a recent study of pre-professional ballet dancers classified the majority of injuries as S1 (activity modification), this only included overuse injuries of the lumbar spine and lower limb which is likely to contribute to this difference.\(^3\)

### Relationship between dance exposure and injury risk

A significant finding in this study was that the total number of dance exposures was found to be more highly associated with injury risk than the total hours of dance exposure. There is considerable potential for variation in volume, intensity, technical demand and nature of exposures during a dancers day/week/term and year.\(^69\) It may be hypothesized that this can result in significant fluctuations in demand, over training or indeed under training the dancer and, hence, contribute to injury risk. Optimizing dance schedules using periodization have been reported to be an effective strategy in reducing injury risk and drop out rates in a pre-professional dance school,\(^70\) and to improve mood states prior to performance in professional dancers.\(^31\) The findings of this research support further investigation into strategies to optimize training outcomes and minimizing injury risk for pre-professional dancers.\(^30,34,69\)

Current evidence indicates that rapid changes in training load precede the onset of injury.\(^29,71\) This is consistent with findings in this study, whereby a greater number of reported injuries were sustained in term one (after the holiday period), peaking again after returning from each semester break. Current literature suggests that high acute:chronic workload ratios may contribute to increased risk of injury.\(^71,72\) Although further research is necessary, this may be a factor contributing to the findings in this study. This study found the number of reported injuries decreased as the year progressed despite a relatively consistent volume of exposure each term.

### Table 6. Association between the total number of reported injuries and risk factors

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Adjusted R Square</th>
<th>B</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>-0.016</td>
<td>-0.001</td>
<td>-0.235 – 0.233</td>
<td>0.992</td>
</tr>
<tr>
<td>BMI</td>
<td>-0.013</td>
<td>0.039</td>
<td>-0.141 – 0.220</td>
<td>0.667</td>
</tr>
<tr>
<td>Gender</td>
<td>-0.014</td>
<td>0.125</td>
<td>-0.817 – 0.567</td>
<td>0.720</td>
</tr>
<tr>
<td>Major</td>
<td>-0.014</td>
<td>-0.100</td>
<td>-0.774 – 0.575</td>
<td>0.769</td>
</tr>
<tr>
<td>Year of training</td>
<td>0.008</td>
<td>-0.272</td>
<td>-0.714 – 0.169</td>
<td>0.222</td>
</tr>
<tr>
<td>Total MCS score</td>
<td>0.022</td>
<td>-0.081</td>
<td>-0.186 – 0.023</td>
<td>0.125</td>
</tr>
<tr>
<td>Mean MCS score</td>
<td>0.054</td>
<td>-0.702</td>
<td>-1.354 – 0.050</td>
<td>0.035*</td>
</tr>
<tr>
<td>Previous Injury</td>
<td>0.016</td>
<td>-0.685</td>
<td>-1.646 – 0.277</td>
<td>0.160</td>
</tr>
</tbody>
</table>

*Statistically significant at p ≤ 0.050
Unlike previous research, assessments periods and increased exposure to rehearsal and performance (at the end of the year) did not result in a higher number of reported injuries.\textsuperscript{16,30} It may be that as the year progressed dancers were better conditioned to meet their demands and therefore more resilient and accustomed to the workload, or simply reported fewer injuries to avoid missing vital assessment and performance opportunities.\textsuperscript{73} In contrast to previous research, the year of pre-professional training was not associated with increased injury risk, despite increasing dance exposure.\textsuperscript{7} It is possible that emerging adolescent dancers have a lower threshold for injury, as has been reported for other sports.\textsuperscript{74} The small cohort and, specifically, the limited number of third year dancers in this study may have contributed to this finding. Further research investigating the dose-response relationship between training and injury and workload ratios across differing age groups and genres is needed.

**Relationship between injury and risk factors**

A primary aim of this study was to establish the relationship between the Movement Competency Screen (MCS), and injury risk. MCS scores were analyzed both as a continuous (total MCS score) and categorical (mean MCS score) variables. The mean (and median) MCS score for this cohort was 23, and this was used to define the categorical variables group assignment (1 = < 23, 2 = ≥23). Those dancers who scored below the mean (<23) were considered to demonstrate reduced or altered movement control during functional movement patterns, beyond that which was typically seen within the cohort. Utilizing the mean MCS score as a cut off score enabled comparisons with previous research of movement screening tools, which have also utilized dichotomized pass/fail scores. In this study dancers who scored less than 23 were more likely to sustain an injury than those who scored at or above 23 (\(p = 0.035\)). This suggests that those dancers who demonstrated reduced or altered movement control during functional movement patterns, beyond what was typically seen within the cohort, may be more susceptible to future injury. This provides some support for the inclusion of the MCS as part of an overall injury screening strategy, whereby those dancers who may benefit from further assessment, conditioning or load modification can be identified in a timely manner. No other studies utilizing the MCS, inclusive of dynamic jump tasks, were identified in the literature, although a recent prospective study of elite rowers in New Zealand did investigate the relationship between the total MCS score (five fundamental movements only) and risk of lower back injury.\textsuperscript{51,75} The authors of that study found rowers who scored at or higher than the mean MCS score were more likely to develop low back pain compared to those who scored lower; however, this finding was not statistically significant (OR = 2.57, \(p = 0.07\)). Studies evaluating the efficacy of other functional movement screening tools to identify those at risk of injury have also reported positive associations. The most reported tool to do so is the Functional Movement Screen (FMS\textsuperscript{TM}),\textsuperscript{76-80} In spite of this, the efficacy of the FMS\textsuperscript{TM} to predict injury risk should be considered in the context of those studies where no association and bimodal associations have been found.\textsuperscript{81-83} The variability presented within the research highlights the difficulty of utilizing cut-off scores for predicting injury risk, where the sensitivity of the cut-off score is inversely related to the specificity.\textsuperscript{84} While a single screening tool alone is unlikely to identify all those at risk of injury, identifying the most effective and efficient tools which detect factors that contribute to the injury risk profile of dancers is essential. The MCS has the potential to be utilized more widely by dance teachers, strength and conditioning coaches, and healthcare providers, and to educate dancers as part of an injury prevention strategy.

The findings of this study support the development of injury prevention programs targeting neuromuscular control in those with identified deficits. A recent three-year prospective study utilized the functional movement screen (FMS\textsuperscript{TM}) to guide the development of individualized conditioning programmes for a group of professional ballet dancers.\textsuperscript{85} This resulted in a significant reduction in all injuries as well as recurrent injury over the three years. As injury prevalence has been shown to be high amongst adolescent dancers, specifically lower limb injuries, injury prevention programmes involving neuromuscular control aimed at the broader adolescent dance population may have the biggest impact in reducing injury risk.
Limitations of the study
Interpretation of these results should be considered alongside the following methodological limitations. The sample size in this study was small due to the limited number of dancers attending the dance school, and as a result the relationship between some risk factors and injury is unclear.86 The loss of five dancers during the course of the study may have also affected observed associations. Furthermore, although statistical analysis demonstrated an association between the mean MCS score and injury, there are still a lot of unknown factors that contribute to these injuries. This was highlighted by the very low adjusted R-squared value ($R^2 = 0.054$) (see Table 6). Further research is therefore still required to identify other possible risk factors for these injuries. The number of days of modified activity for time-loss injuries was not included and should be taken into consideration when interpreting the impact and severity of time-loss injuries on dance participation. The intensity and nature of dance exposures, and workload ratios was not included in exposure analysis. These factors may impact on the potential injury risk of individual dancers. Dance exposure was calculated each week from the timetables, for each year group (major and gender), but not individually, hence may not truly reflect the actual hours of training or engagement by each individual dancer. Non-scheduled dance practice or additional workouts such as attending the gym, were also not included in the total hours of dance. As the dancers progressed through the year their movement competency may have changed, and also their injury risk in relation to MCS scores. Research undertaking screening at more regular intervals over the year may better establish the relationship between outcomes scores and injury risk.

Functional movement screening has the capacity to identify dancers at risk of injury. As such, future intervention studies targeting those at risk individuals/groups with focused prevention/conditioning programmes are indicated. Multicentre studies examining training loads (acute and chronic) and nature of exposures in relation to injury risk are necessary to optimise training and performance outcomes across differing age groups and genres. Future research is needed to examine if MCS scores taken at regular intervals during the year may be more useful in establishing injury risk. Research establishing the inter-rater reliability of the MCS is necessary for this tool to be useful between providers and across the broader population.

CONCLUSION
This is the first prospective longitudinal study of pre-professional dancers in New Zealand. Injury prevalence and incidence rates were high, although comparable to those reported internationally. The results of this study indicate, that the number of dance exposures was more highly associated with injury risk than the hours of dance exposure. Furthermore, dancers had a greater risk of sustaining injury in term one, reducing with each term of the year. There is a need for further prospective longitudinal studies examining dance exposure and the relationship to injury. An MCS score < 23 was associated with an increased risk of future injury. Therefore, including the MCS as part of an overall injury screening strategy may be an efficient and effective strategy to help identify those dancers who could benefit from focused injury prevention strategies.

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APPENDIX 1

Reported Injury Summary Sheet

Dancers Name: __________________________ DOI: __________________________

1. Injury Type

☐ New  ☐ Recurrent (re-injury/exacerbation) (circle which applies)

2. Injury Cause

☐ Trauma  ☐ Overuse  Occurred During: (circle) ballet, contemporary, other___________

3. Is this a time-loss injury?

☐ Yes (Go to question 4, 7-9)
☐ No  The dancer is still able to participate (Go to questions 5-9)

4. If the dancer has sustained a time-loss injury and is/was not able to dance please state the date the dancer stopped dancing and when they returned to dance.

☐ _____________ (date stopped dance)  or  ☐ Estimated number of full days off dance

☐ _____________ (date resumed dance)

5. If the dancer did NOT take time off due to their injury to what extent did they have to reduce/modify training load during this injury?

☐ Not at all  ☐ Minor  ☐ Moderate  ☐ Major

6. How many days did the dancer have to modify their dance training load due to this injury?

☐ _____________ (total number of days of modified training)

OR

☐ _____________ (estimated number of modified training)

7. Injury location

☐ __________________________

8. Injury diagnosis (Preliminary/Final)

☐ __________________________

9. Treatment Provider/s

☐ Physio  ☐ Sports Physician  ☐ Investigation (x-ray/MRI/US)

☐ Other (Specify)

Approved by the Auckland University of Technology Ethics Committee on 23 September 2013 AUTEC Reference number 13/245
Injury severity was measured by time-loss (days) or degree of activity modification and were defined as:

**Time-loss:** is the total number of full days off dance, from the date of injury to the date of the dancer returning to participation.57

**Activity Modification:** is the extent to which a dancer had to modify or reduce their training load due to injury. This was rated using a descriptive scale, describing the degree of activity modification the dancer had to undertake as a result of the injury as listed below.

1. **Not at all:** dancer is able to attend all classes/rehearsals/performance, without any limitations
2. **Minor:** dancer is able to attend all classes/rehearsals/performance with only minor limitations
3. **Moderate:** dancer is able to attend all classes/rehearsals/performance but with moderate limitations such as; participating in petite allegro but not grand allegro, keeping legs below 45 degrees
4. **Major:** dancer is unable to participate in significant components of classes/rehearsals/performance, including having to sit out some but not all timetabled classes over a normal school day or avoiding significant components such as jumping or pointe work

Injury severity was also coded based on definitions adapted from previous research by Dick, Agel, Marshall57 and Bowerman64

S0 No days off or modified
S1 Activity modification only
S2 ≤ 7 days off dance
S3 > 7 days off dance
S4 Year ending - if a dancer was unable to return to training due to injury
### APPENDIX 3

**Movement Competency Screen Testing Sequence**

<table>
<thead>
<tr>
<th>Order of MCS and verbal instructions for each of the MCS movement tasks</th>
<th>Make sure to get a video from the front and side views for each MCS task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bodyweight Squat</td>
<td></td>
</tr>
<tr>
<td>2. Counter movement Jump (CMJ)</td>
<td></td>
</tr>
<tr>
<td>Bodyweight Squat: Perform a body weight squat with your fingertips on the side of your head and your elbows held inline with your ears. Squat as low and as fast as you comfortably can. CMJ: With your fingertips on the side of your head and your elbows held inline with your ears, jump as high as you can.</td>
<td></td>
</tr>
<tr>
<td>3. Lunge and Twist at self selected speed (Right)</td>
<td></td>
</tr>
<tr>
<td>4. Lunge and Twist at self selected speed (Left)</td>
<td></td>
</tr>
<tr>
<td>5. Lunge and Twist as fast as possible (Right)</td>
<td></td>
</tr>
<tr>
<td>6. Lunge and Twist as fast as possible (Left)</td>
<td></td>
</tr>
<tr>
<td>7. Bilateral broad jump with unilateral land (Right)</td>
<td></td>
</tr>
<tr>
<td>8. Bilateral broad jump with unilateral land (Left)</td>
<td></td>
</tr>
<tr>
<td>Lunge and Twist: Cross your arms and place your hands on your shoulders with your elbows pointing straight ahead. Perform a forward lunge then rotate toward the forward knee. Return to center and then push back to return to the starting position. Alternate legs with each repetition</td>
<td></td>
</tr>
<tr>
<td>Broad Jump with unilateral land: Perform a broad jump with a two-foot take off and a one-foot land.</td>
<td></td>
</tr>
<tr>
<td>9. Bodyweight single leg squat (Right)</td>
<td></td>
</tr>
<tr>
<td>10. Bodyweight single leg squat (Left)</td>
<td></td>
</tr>
<tr>
<td>11. CMJ off two legs with a single leg land on the right</td>
<td></td>
</tr>
<tr>
<td>12. CMJ off two legs with a single leg land on the left</td>
<td></td>
</tr>
<tr>
<td>Single Leg Squat: Perform a single leg body weight squat with your fingertips on the side of your head your elbows in line with your ears. Position the non-stance leg behind your body as you squat. Squat as low and as fast as you comfortable can. CMJ with unilateral land: Perform a jump squat with a two-foot take off. Jump as high as you can. Land on only one foot.</td>
<td></td>
</tr>
<tr>
<td>13. Bend and Pull at self selected speed</td>
<td></td>
</tr>
<tr>
<td>14. Bend and Pull as fast as possible</td>
<td></td>
</tr>
<tr>
<td>Bend &amp; Pull: Start with your arms stretched overhead. Bend forward allowing your arms to drop under your trunk. Pull your hands into your body as if you were holding onto a bar and performing a barbell rowing exercise. Return to the start position with your arms stretched overhead. Bend &amp; Pull at speed: Perform the bend and pull as fast as you possibly can.</td>
<td></td>
</tr>
<tr>
<td>15. Push Up</td>
<td></td>
</tr>
<tr>
<td>16. Explosive Push UP</td>
<td></td>
</tr>
<tr>
<td>Push Up: Perform a standard push up. Explosive Push Up: Perform a fast pushup and try to lift your upper body off the ground.</td>
<td></td>
</tr>
</tbody>
</table>

---

* The movement was performed a total of six times (three time facing the front and three times facing the side)

** The explosive tasks (Exercises 14 and 16) were not included in the screening assessment
APPENDIX 4

<table>
<thead>
<tr>
<th>Test</th>
<th>Primary</th>
<th>Secondary</th>
<th>Load Level</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squat</td>
<td>Head</td>
<td>Lumbars</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knees</td>
<td>Hips</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Lunge &amp; Twists Left</td>
<td>Head</td>
<td>Lumbars</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knees</td>
<td>Hips</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Lunge &amp; Twists Right</td>
<td>Balance</td>
<td>Lumbars</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knees</td>
<td>Hips</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Bend &amp; Pull</td>
<td>Shoulders</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Knees</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Ankle</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Balance</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Push Up</td>
<td>Shoulders</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Knees</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Ankle</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Balance</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Single Leg Squat Left</td>
<td>Depth</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Shoulders</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Knees</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Single Leg Squat Right</td>
<td>Depth</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Shoulders</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Knees</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Jump &amp; Land (both feet)</td>
<td>Shoulders</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Knees</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Ankle</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Vertical Jump &amp; Land - jump off two land on left</td>
<td>Depth</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Shoulders</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Knees</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Vertical Jump &amp; Land - jump off two land on right</td>
<td>Depth</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Shoulders</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Knees</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Broad Jump &amp; Land - jump off two land on left</td>
<td>Depth</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Shoulders</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Knees</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Broad Jump &amp; Land - jump off two land on right</td>
<td>Depth</td>
<td>Head</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lumbars</td>
<td>Shoulders</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips</td>
<td>Knees</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>Ankle</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Movement Competency Score (out of 36) < 20 = Poor; 21-30 = Moderate; > 30 = Good
## APPENDIX 5

### Movement Competency Screen Scoring Criteria

<table>
<thead>
<tr>
<th>Body Region/Capacity</th>
<th>MCS Task 1 Body Weight Squat</th>
<th>MSC Task 2 Counter Movement Jump</th>
<th>MSC Task 3 Lunge and Twist</th>
<th>MCS Task 4 Bilateral broad jump with unilateral land</th>
<th>MCS Task 5 Body weight single leg squat</th>
<th>MCS Task 6 Counter movement jump off two landing on one</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shoulders held down away from ears. Elbows in line with ears.</td>
</tr>
<tr>
<td><strong>Shoulders</strong></td>
<td>Held down and away from ears.</td>
<td>Held down away from ears. Elbows in line with ears.</td>
<td>Held down and away from ears. Elbows in line with ears. Rotation appears to occur through thoracic spine. Elbows is at least inline with the lead knee at end range of rotation</td>
<td>Held down away from ears.</td>
<td>Held down away from ears. Elbows in line with ears. Thoracic extension is clear</td>
<td>Shoulders held down away from ears. Elbows in line with ears.</td>
</tr>
<tr>
<td><strong>Lumbar</strong></td>
<td>Neutral curve</td>
<td>Maintains lumbar curve, no hyperextension, rotation or flexion</td>
<td>Held stable, neutral spine is maintained through out rotation. Rotation and/or lateral flexion does not occur about the lumbar region during trunk rotation</td>
<td>Maintains lumbar curve, no hyperextension, rotation or flexion</td>
<td>Held stable in a neutral spine position throughout lower limb flexion and extension</td>
<td>Maintains lumbar curve, no hyperextension, rotation or flexion</td>
</tr>
<tr>
<td><strong>Hips</strong></td>
<td>Movement is initiated with hip flexion. Remain horizontally aligned during flexion and extension. Obviously moving back and down during flexion</td>
<td>Horizontally aligned, mobile and stable to prohibit elevation and depression during rotation</td>
<td>Horizontally aligned and stable to minimize elevation and depression during landing</td>
<td>Movement is initiated with hip flexion. Remain horizontally aligned during flexion and extension. Clearly moving back and down during flexion, minimal weight shift over stand leg.</td>
<td>Aligned with the hip and foot during flexion and extension</td>
<td>Aligned with hips and feet</td>
</tr>
<tr>
<td><strong>Knees</strong></td>
<td>Aligned with hips and feet during flexion</td>
<td>Aligned with hips and feet during flexion and do not move laterally with rotation</td>
<td>Aligned with hips and feet</td>
<td>Aligned with the hip and foot during flexion and extension</td>
<td>Aligned with hips and feet</td>
<td>Aligned with hips and feet</td>
</tr>
<tr>
<td><strong>Ankles</strong></td>
<td>Mobility allow adequate dorsiflexion during knee and hip flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Feet</strong></td>
<td>Stable with heels grounded during lower limb flexion</td>
<td>Heel of lead leg in contact with the floor, trail foot flexed and balanced on forefoot</td>
<td>Stable</td>
<td>Stable with heels grounded during lower limb flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Balance</strong></td>
<td>Evenly distributed</td>
<td>Maintained on each leg</td>
<td>Able to control and stick landing</td>
<td>Maintained on each leg</td>
<td>Able to control stick landing</td>
<td></td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>90 degrees or greater of hip flexion</td>
<td>70 degrees or greater of hip flexion</td>
<td>Lead thigh parallel to the floor</td>
<td>70 degrees of hip flexion</td>
<td>70 degrees of hip flexion</td>
<td>70 degrees of hip flexion</td>
</tr>
</tbody>
</table>
## Movement Competency Screen Scoring Criteria

<table>
<thead>
<tr>
<th>Body Region/Capacity</th>
<th>MCS Task 7 Bend and Pull</th>
<th>MSC Task 8 Press up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Held stable in a neutral position</td>
<td>Held down from ears during arm flexion and extension. Scapulae move balanced and rhythmic and are not excessively abducted at arm extension</td>
</tr>
<tr>
<td>Shoulders</td>
<td>Held down away from ears during arm flexion and extension. Scapulae move balanced and rhythmic and are not excessively abducted at arm extension</td>
<td>Held down and away from ears during arm flexion and extension. Scapulae move balanced and rhythmic and are not excessively abducted at arm extension</td>
</tr>
<tr>
<td>Lumbar</td>
<td>Held stable in neutral spine position throughout trunk flexion and extension</td>
<td>Held in stable neutral spine position</td>
</tr>
<tr>
<td>Hips</td>
<td>Movement is initiated with hip flexion. Extension is obvious and controlled</td>
<td>Held in line with the body during arm flexion and extension</td>
</tr>
<tr>
<td>Knees</td>
<td>Neutral position and held stable</td>
<td>Extended and held stable</td>
</tr>
<tr>
<td>Ankles</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Feet</td>
<td>Pointing straight</td>
<td>Feet straight, heels not falling in or out</td>
</tr>
<tr>
<td>Balance</td>
<td>Maintained</td>
<td>NA</td>
</tr>
<tr>
<td>Depth</td>
<td>75 - 90 degrees or greater of trunk flexion</td>
<td>Chest touches floor</td>
</tr>
</tbody>
</table>

Adapted from Kritz (34), Kritz (35,39) and Vanweerd (47)
ABSTRACT

Background: Training intensity is an important variable in strength training and above 80% of one repetition maximum is recommended for promoting strength for athletes. Four dynamic and two isometric on-field exercises are included in the Hölmich groin-injury prevention study that initially failed to show a reduction in groin injuries in soccer players. It has been speculated that exercise-intensity in this groin-injury prevention program was too low to induce the strength gains necessary to protect against groin-related injuries.

Purpose: To estimate the intensity of the six exercises from the Hölmich program using electromyography (EMG) and possibly categorize them as strength-training exercises.

Study Design: Cross-sectional study.

Methods: 21 adult male soccer players training >5 hours weekly were included. Surface-EMG was recorded from adductor longus, gluteus medius, rectus abdominis and external obliques during isometric adduction against a football placed between the ankles (IBA), isometric adduction against a football placed between the knees (IBK), folding knife (FK), cross-country skiing on one leg (CCS), adduction partner (ADP) and abduction partner (ABP). The EMG-signals were normalized (nEMG) to an isometric maximal voluntary contraction for each tested muscle.

Results: Adductor longus activity during IBA was 84% nEMG (95% CI: 70-98) and during IBK it was 118% nEMG (95% CI 106-130). For the dynamic exercises, ADP evoked 87% nEMG (95% CI 69-105) in adductor longus, ABP evoked 88% nEMG (95% CI 76-100) in gluteus medius, FK evoked 82% nEMG (95% CI 68-96) rectus abdominis, and 101% nEMG (95% CI 85-118) in external obliques. During CCS <37% nEMG was evoked from all muscles.

Conclusion: These data suggest that exercise-intensity of all the six investigated exercises in the Hölmich groin injury prevention program, except cross-county skiing, is sufficient to be considered strength-training for specific muscle groups in and around the groin region.

Level of Evidence: 3

Key words: Abdominals, adductor longus, electromyography, gluteus medius, soccer

Acknowledgements

The authors would like to thank all the players who took the time to participate in the study, as well as the team of physiotherapy students Jonas Nesse-Karlsen, Kaare Mejding and Kaare Frandsen for help with the practical work during the tests.

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INTRODUCTION
Groin injuries are one of the most common types of injuries in soccer, accounting for 8-18% of all injuries.1–3 Groin injuries in soccer are primarily related to the hip adductors, accounting for approximately 60% of all acute and long-standing groin injuries, but can also be related to varied anatomical locations/tissues, such as the hip flexors, the abdominal muscles, and the inguinal canal.3–5

The latest systematic reviews on risk factors for groin injuries concluded that there is relatively consistent Level 1 and 2 evidence to suggest that hip adductor and abductor strength is associated with increased risk of groin injury.6–7 A randomized controlled trial by Hölmich et. al.8 concerning injury prevention of groin injuries in soccer included exercises targeting these risk factors by performing a comprehensive exercise program focusing on strength and stability. The trial included nearly 1000 players and was aimed at reducing groin injury rates by 50%, however, only a 30% non-significant difference in injury rates was found.8 One of the possible reasons for the lack of an intended effect (≥50% reduction) on the prevention of groin injuries in soccer has been suggested to be related to a lack of adequate intensity of the included exercises.8

To promote strength gains in athletes, it is recommended to recruit the entire pool of motor units, based on the size principle.9–11 The threshold for high-threshold motor units varies for different muscles, with small muscles, such as muscles of the fingers, requiring as little as 30% of maximum effort to reach total recruitment,12 and larger muscles, such as the tibialis anterior and biceps brachialis, having thresholds at 80% and 90%, respectively.12,13 In that respect, intensity is recommended to be at least 80% of one repetition maximum (RM) for a stimulus that can induce strength gains in athletes.9 As opposed to joint-torque or external load of a given exercise, EMG (electromyography) is often used to quantify exercise intensity of specific muscles by measuring the recruitment and firing characteristics during exercise.14–19 In that respect, longitudinal strength gains have been repeatedly found when utilizing exercises at above 80% EMG intensity,19–24 as a quasi-linear relationship between EMG and force output has been described.14–16,25–28 Thus, EMG normalized (nEMG) to a maximal voluntary isometric contraction30 (MVC) with correct electrode placement14,15 and in a non-fatigued state15,16,28 is suggested as a valid option when estimating exercise intensity of specific muscles,14–19 with 80% of maximum as the rough cut-off required to promote strength gains in athletes.9

Six exercises were included in the Hölmich prevention program of which the two isometric exercises were shown in a previous investigation to produce high levels of muscle activity (nEMG values > 80%) in the adductor longus.19 However, resistance training is recommended to include dynamic muscle contractions9,31,32 and no information exists on the specific intensity of the dynamic exercises in the prevention program introduced by Hölmich et al.8 Considering that the dynamic exercises in the program require no use of additional equipment for resistance, compared to weight training machines, free weights, elastic bands or other forms of exercise equipment that help quantify intensity, it may be that these exercises do not induce sufficient intensity to promote strength gains in soccer players.

The purpose of this study was therefore to estimate the intensity of the six exercises from the Hölmich program using electromyography (EMG) and possibly categorize them as strength-training exercises.

METHODS
Study design
The present study used a cross-sectional design in which participants were investigated once having been familiarized with the trial procedures on a previous occasion. During the first session, they performed a 10-min. standardized warm-up of running drills and mobility exercises and were subsequently familiarized with all the exercises. The second session was conducted at least four days after to avoid delayed onset of muscle soreness. After the same standardized warm-up, the subjects performed MVCs to be used as reference contractions followed by two trials of the six exercises in a random order with minimum 60 s between, while muscle activity was recorded using surface EMG. Participants rated the level of perceived exertion during all exercises on the BorgCR10-scale, a categorical numeric rating scale with verbal anchors ranging from 0 ~
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‘Nothing at all’ to 10 ~ ‘Extremely strong’ to provide additional data on subjective intensity. No exercise or training was allowed the day before testing and both sessions took place at Hvidovre Hospital, Copenhagen, Denmark. The reporting of the study follows the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines, using the checklist for cross-sectional studies and was approved by the Danish National Committee on Health Research Ethics (H-3-2011-145.). All participants gave written consent according to the Helsinki Declaration before testing was initiated. The study is not pre-registered.

Participants
Through convenience sampling, participants were recruited on a voluntary basis through contacts from local rugby and soccer clubs in Copenhagen, Denmark, from March to June 2012. Players were eligible for inclusion if they did not have injuries which could be presumed to influence the execution of the exercises, and had no or only minimal self-reported hip or groin pain, indicated by a score of above 80 out of 100 on the Hip and Groin Outcome Score (Sports subscale).33

The six exercises from the Hölmich groin-injury prevention program
The present study included two isometric and four dynamic exercises introduced by Hölmich et al.8 Three repetitions of each dynamic exercise were used for analysis of the EMG signal in order to reduce the accumulation of fatigue. The isometric exercises were performed for 10 s, as described by Hölmich et al.8

1: Isometric adduction against a soccer ball placed between the ankles (IBA): when lying supine, the thigh in neutral position, applying pressure against the ball as hard as possible (Figure 1a).8

2: Isometric adduction against a soccer ball placed between the knees (IBK): when lying supine with flexed hips and knees and feet flat on the surface, the thigh in neutral position, applying pressure against the ball as hard as possible (Figure 1b).8

3: ‘Folding knife’ (FK): a combined abdominal sit-up and hip flexion. Starting from the supine position, with a football between flexed knees, repetitions are performed in a slow pace by flexing the hip and the lower back, bringing knees and chest together (Figure 1c).8

4: Standing one-leg coordination exercise called “cross-country skiing on one leg” (CSS): flexing and extending the knee and swinging the arms in the same rhythm, repetitions are performed on the dominant leg (defined as the preferred kicking leg) as the standing leg (Figure 1d).8

Exercises
5 and 6 are partner exercises where two players perform both exercises together simultaneously:

5: Hip adduction against a partner’s hip abduction called “adduction partner” (ADP): in the sitting position, supported by the hands placed on the ground behind the trunk, the tested player places his legs straight and wide apart with the feet and lower shin on the outside of the partner’s feet and lower shin. He adducts while the partner abducts eccentrically and slowly presses his feet together (Figure 1e).8

6: Hip abduction against a partner’s hip adduction called “abduction partner” (ABP): from the reversed starting position as “adduction partner” with feet and lower shins now placed medially on his partner’s feet and lower shin, the player abducts concentrically (“abduction partner”) while the partner adducts eccentrically, and is slowly brought into abduction (Figure 1f).8

Both partner-exercises were performed for 6 seconds per repetition with a 3 s concentric and a 3 s eccentric contraction, with as much effort as possible, still allowing the partner to follow the tempo for the duration of the exercise.8

ELECTROMYOGRAPHY (EMG)
Rectangular (20 x 30 mm) non-disposable differential surface-electrodes with 1 cm inter-electrode distance (DE-2.1, Delsys, Boston, MA, USA) were placed unilaterally to collect data from adductor longus, gluteus medius, rectus abdominis and the external oblique muscles after standard skin preparation. Using electrode gel and medical grade adhesive (Delsys electrode interface, Delsys, Boston, MA, USA), the electrodes were aligned parallel with the direction of the muscle fibres. Verification of EMG signal quality was conducted by visual inspection of...
the raw EMG signal while the subjects performed movements similar to the six evaluated exercises and isometric contractions specific to each muscle of interest after initial electrode placement and again after the warm-up routine. The electrodes were attached to 150 cm shielded wires, connected directly to small built-in preamplifiers and further to a main amplifier unit (Bagnoli-16, Delsys, Boston, MA, USA) with a band-pass of 15–450 Hz and a common-mode rejection ratio of 92 dB. Sampling was done at 1 kHz using a 16-bit A/D converter (6036E, National Instruments, Austin, TX, USA). Data analysis was performed on a personal computer (EMGworks acquisition 3.1, Delsys, Boston, MA, USA).

Electrode placements
Adductor longus; medially on the thigh equivalent to the proximal third of the distance from the

Figure 1. The six included exercises: a = “isometric adduction against a football placed between the ankles”; b = “isometric adduction against a football placed between the knees”; c = “folding knife”; d = “crosscountry skiing on one leg”; e = “adduction partner” performed by the player to the left; f = “abduction partner” performed by the player to the left.
A ball placed between the knees. *Gluteus medius MVC;* side-lying with hip and knees straight, the tested leg is held in approximately 25 degrees of hip abduction by the therapist. An isometric hip abduction was performed against a belt fixed around the lateral femoral epicondyle, as the use of belts has been shown to be less demanding on the therapist, preferred by participants and increases the reliability of maximal hip abduction torque measurements. *Rectus abdominis and external obliques;* a lumbar spine flexion with isometric abdominal contraction in a supine position against a fixed training belt strapped around the chest.

### Data reduction

The raw EMG signals were visually inspected and contractions with signal artifacts were discarded. All raw EMG signals were digitally filtered using a Butterworth 4th order high-pass filter (10 Hz cutoff frequency), and subsequently smoothed and filtered using a moving root-mean-square (RMS) filter of 500 ms. Peak EMG of each muscle within each contraction was identified as the maximum value of the smoothed RMS EMG signal and normalized to the maximal RMS EMG obtained during the MVC.

### Statistical methods

Based on a mean of 108% nEMG and a 35.5% standard deviation from a previous investigation of the IBK exercise, a significance level of 0.05 and statistical power of 80% to detect differences of 20% between muscles and exercises, a sample of 21 participants was needed based on the paired t-test (G*Power 3.1.9.2). All Borg CR10 values are presented as medians with interquartiles ranges and their corresponding verbal anchors. All nEMG values are reported as least square means with 95% confidence intervals (CI). A repeated measures one-way analysis of variance (ANOVA) with a significance level of p ≤ 0.05 was used to compare the peak nEMG for each muscle in the different exercises, in order to compare all exercises to each other. The mean of peak from all three repetitions was used for the dynamic exercises. A Bonferroni correction was made to account for the multiple comparisons in the post hoc analysis. All analyses were performed for participants with complete data sets (per protocol) and no imputations were made.
all other exercises (p<0.001), and rectus abdominis and external obliques activation in the FK was higher than in all other exercises (p<0.001). The levels of perceived exertion rated on the BorgCR10 scale during exercises ranged from 'Weak' to 'Strong', with CSS being perceived as 'Weak' (median 2.5, IQR 1.1-3.75), ABP as 'Moderate' (median 4, IQR 3-6) and the remaining exercises as 'Strong' (ADP median 5, IQR 4-6.75; FK median 5, IQR 3-6.75; IBA median 5, IQR 3-7; IBK: median 5, IQR 4.25-6.75).

DISCUSSION
The main purpose of this study was to examine the level of muscle activity during two isometric and four dynamic strengthening exercises from a previously published groin-injury prevention program.8 The two isometric exercises have previously been investigated for muscle activity and showed similar levels as in the current study with both ≥80% nEMG.19 The levels of perceived exertion rated on the BorgCR10 scale during exercises ranged from 'Weak' to 'Strong', with CSS being perceived as 'Weak' (median 2.5, IQR 1.1-3.75), ABP as 'Moderate' (median 4, IQR 3-6) and the remaining exercises as 'Strong' (ADP median 5, IQR 4-6.75; FK median 5, IQR 3-6.75; IBA median 5, IQR 3-7; IBK: median 5, IQR 4.25-6.75).

RESULTS
Twenty-four healthy male soccer and rugby players were enrolled in the study. Data from three participants were missing due to broken reference electrodes, excessive artifacts or erroneous data extraction. The decision to exclude these data was made prior to the data analyses. Thus, the comparative analysis included 21 participants, mean age 21.4 ± 3.3 y, height 182.1 ± 7.7 cm, weight 83.1 ± 13.4 kg and scoring 96.7 ± 5.2 points on the HAGOS (Sports subscale). The participants had a training frequency of 5.2 (± 1.1) hrs per week with 1-2 weekly matches.

EMG activation levels are presented in Table 1. Five exercises reached specific muscle activation levels above 80% nEMG. In the isometric exercises, IBA muscle activity of the adductor longus was 84% nEMG (95% CI 70-98) and during IBK it was 118% nEMG (95% CI 106-130). With respect to the dynamic exercises, ADP evoked 87% nEMG (95% CI 69-105) in adductor longus, in the ABP exercise gluteus medius was reached 88% nEMG (95% CI 76-100), for the FK rectus abdominis was 82% nEMG (95% CI 68-96), and external obliques was 101% nEMG (95% CI 85-118). During CSS all muscles were <37% nEMG. In the two isometric exercises, the adductor longus muscle activity was greater than in all other muscles, with greatest activity in the IBK (p<0.0001). For the dynamic exercises, the adductor longus activation was higher in the ADP exercise than in all other dynamic exercises (p<0.001). Gluteus medius activation was greater in the ABP exercise, than in all other exercises (p<0.001), and rectus abdominis and external obliques activation in the FK was higher than in all other exercises (p<0.001). The levels of perceived exertion rated on the BorgCR10 scale during exercises ranged from 'Weak' to 'Strong', with CSS being perceived as 'Weak' (median 2.5, IQR 1.1-3.75), ABP as 'Moderate' (median 4, IQR 3-6) and the remaining exercises as 'Strong' (ADP median 5, IQR 4-6.75; FK median 5, IQR 3-6.75; IBA median 5, IQR 3-7; IBK: median 5, IQR 4.25-6.75).

DISCUSSION
The main purpose of this study was to examine the level of muscle activity during two isometric and four dynamic strengthening exercises from a previously published groin-injury prevention program.8 The two isometric exercises have previously been investigated for muscle activity and showed similar levels as in the current study with both ≥80% nEMG.19 The results of the current study indicate that three of the dynamic exercises in the groin injury prevention program can be categorized as exercises with sufficient intensity for strength improvements in athletes, targeting important muscle groups relevant in the prevention of groin injuries; adduction partner for adductor longus, abduction partner for gluteus medius, and folding knife for rectus abdominis and external obliques. These muscles are important as most groin injuries are related to the adductor longus but may also be related to the abdominal muscles and the inguinal canal.3-5 Authors of several studies6,7

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### Table 1. Peak normalized EMG measurements for all exercises and muscles

<table>
<thead>
<tr>
<th>Muscle Group</th>
<th>Isometric</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IBA</td>
<td>IBK</td>
</tr>
<tr>
<td>Adductor longus</td>
<td>84 (7)*</td>
<td>118 (6)*</td>
</tr>
<tr>
<td>Gluteus medius</td>
<td>11 (2)</td>
<td>11 (2)</td>
</tr>
<tr>
<td>Rectus abdominis</td>
<td>8 (2)</td>
<td>4 (1)</td>
</tr>
<tr>
<td>External obliques</td>
<td>19 (4)</td>
<td>14 (4)</td>
</tr>
</tbody>
</table>

Values reported as mean normalized electromyography (standard error). IBA = “isometric adduction against a football placed between the ankles”; IBK = “isometric adduction against a football placed between the knees”; FK = “folding knife”; CSS = “cross-country skiing on one leg”; ADP = “adduction partner”; ABP = “abduction partner”. * = significantly higher peak nEMG for this muscle than for other muscles during the exercise (p < 0.002). † = significantly higher peak nEMG during this exercise for this muscle than during any other exercise (p < 0.0001).
have identified decreased strength in the adductors preceding and following the onset of groin injuries, which makes adductor strength training a top priority in prevention and rehabilitation of groin injuries. In addition, targeted strengthening around the hip may contribute to pelvic alignment (frontal plane pelvic angle), which has been mentioned as an important factor in both prevention and management of groin injuries. Decreased strength in the hip abductors (gluteus medius) has also been found in athletes who since sustained a groin injury, making hip abductor strength training another key muscle for groin injury prevention. The exercise “cross-country skiing on one leg” did not reach sufficient intensity for strength training but it might promote dynamic stability in single leg stance and pelvic alignment through improved endurance capacity of gluteus medius, especially during minor to moderate and repetitive loading situations, such as in sub-maximal running and change of direction, an intensity also often utilized during a soccer game or practice. Based upon the current data it seems unlikely that inadequate exercise intensity should be the explanation for the lack of a substantial effect (50% groin injury reduction) of such a program in soccer players, as five of the six included exercises have been demonstrated in the current study to be sufficiently intense to promote strength gains in muscles relevant in groin injury prevention. Previous investigations of muscle activity of adductor longus during exercise have shown that muscle activity during the Barbell squat increases if the stance width and external hip rotation is increased. However, the highest nEMG found was only 23.1%. Commonly used unilateral frontal plane exercises for rehabilitation of lower extremity injuries; lunges, step-up and step up-and-over were in another study found to only evoke nEMG of the adductors in the range of 16-22%. Delmore et al. examined several specific hip adductor exercises that showed intensities of 14-36% nEMG. However, one exercise in the study by Delmore et al., resisted side-lying hip adduction showed adductor longus nEMG of 60%, in concordance with previous findings of 64% nEMG from Serner et al., although un-resisted in their study. The relatively low nEMG results found in these studies indicate that exercises in which the adductors are working as stabilizers or hip-extensors such as in during squat variations are not able to induce the same muscle activity as the exercises included in the present study. In comparison the “adduction partner”, although limited by the partner determining and providing the level of resistance, has no need for extra external resistance devices and demonstrated muscle activity similar to exercises previously implemented using strength training equipment such as strength training machines and elastic bands. The dynamic Copenhagen Adduction exercise also relies on partner-assistance, performed sidelying and as the partner holds the upper leg at the height of the hip, the athlete lifts his entire body with using primarily his hip adductors until it reaches a straight line. The Copenhagen Adduction has been shown to induce high muscle activity of 108% of MVC, and longitudinal strength gains. However, isometric exercises induce angle-specific strength gains and are predominantly recommended in the course of muscle injury rehabilitation when pain and range of motion limits the ability to perform dynamic muscle contractions recommended for strength training. Thus, the three dynamic exercises included in the current study in combination with the Copenhagen Adduction exercise seem to be some of the most relevant exercises to include when considering the initiation of a groin injury prevention program, because they evoke muscle activity above 80% opposed to other dynamic equipment-free exercises investigated in the literature. This allows for speculation regarding other possible factors influencing the lack of statistical injury reduction in the previous Hölmich trial. Besides intensity, other important exercise variables could also be part of the explanation, such as frequency, total volume and adherence, which were largely unknown in the trial. Another factor that has recently been shown to have a substantial impact on the risk of injury is the ratio between acute workload (1 week total distance) and chronic workload (4-week average acute workload) during both training and competitive matches in soccer. These two factors should be either controlled for or observed as a potential confounding factor in future trials aimed at preventing injuries in soccer. A substantiating argument for the use of dynamic high intensity exercises for soccer players is that exercises targeting the at-risk muscle with high muscle activity have been able to significantly reduce
other muscle-tendinous injuries, as well as increase strength.\textsuperscript{22,24,56} For example, one study implemented the Nordic Hamstring exercise,\textsuperscript{24,56} which has shown biceps femoris long head nEMG of 91\%\textsuperscript{23} and is performed eccentrically to match the deceleration phase of the leg during running/sprinting, where hamstring injuries often occur.\textsuperscript{56} As such, the exercises from the current study seem highly relevant to implement in future trials aiming at reducing groin injuries.

The Borg\textsuperscript{CR10} scale was used in the current study which is closely related to exercise intensity.\textsuperscript{51,57} Other measures of perceived exertion could also be used in clinical practice, such as the Repetitions in Reserve (RIR) which used for strength training at intensities near repetition-failure, by having the athlete subjectively estimate how many additional repetitions were possible.\textsuperscript{56} As players in the present study only performed three repetitions in order to minimize the presence of fatigue and thereby allowing meaningful interpretations of the EMG data, using RIR would however not be relevant.

**METHODLOGICAL LIMITATIONS**

There are several limitations of using EMG to estimate exercise intensity. For example when using dynamic exercises, the EMG amplitude can be relatively higher than the expected force based on assumptions of a linear force-EMG relationship. The association between EMG and force are also not always linear as the force-velocity and force-length relationship is not accounted for, neither is the electromechanical delay. Nevertheless, using appropriate methods, e.g. using slowly controlled contractions and appropriate analytical methods, there seems to be a good and linear relationship between normalized EMG and percentage of load utilized during 1RM in certain exercises.\textsuperscript{27} The application of surface electrodes carries the risk of crosstalk from adjacent muscles.\textsuperscript{14,15} Accordingly, the muscle activity of adductor longus could possibly reflect the muscle activity of the adductor group as a whole. As muscle activity of more than 100\% nEMG was found during the isometric exercise IBK, which is consistent with previous findings,\textsuperscript{20} thus, it could be assumed that this exercise and position might be more appropriate to perform the MVC in if performed according to MVC guidelines with standardized order, instruction and duration.\textsuperscript{30}

**CONCLUSION**

These data suggest that the exercise intensity of all but one of the six investigated exercises from the previous published Hölmich groin injury prevention program is sufficient to be categorized as strengthening exercises for specific relevant muscle groups in and around the groin region.

**REFERENCES**

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ABSTRACT

Background: One common component of concussion rehabilitation is a computerized cognitive test free of concomitant physical demands. Healthcare professionals may be able to provide more patient-centered care after a diagnosed concussion if specific areas of impairment are identified and treated, such as the physical aspect of neurocognitive function.

Hypothesis/Purpose: To evaluate the test-retest reliability of a unique combination of neurocognitive assessment tools currently utilized in concussion assessments into one single, inclusive instrument that measures both neurocognitive function and physical capability.

Study Design: Original research – diagnostic tests.

Methods: Fourteen individuals (nine males, age: 29 ± 17.9, five females, age: 46.0 ± 21.5 years) either with normal cognitive function (NBI) without history of a health event (e.g. cerebral vascular accident/stroke, mTBI) that resulted in brain injury within one year of the study, or who had suffered a health event that has resulted in a medically documented brain injury (BI) participated in the study. Participants completed the full hybrid assessment instrument for a baseline test, then completed a follow-up test using the same instrument within 72-96 hours of baseline. Test-retest reliability was measured using Pearson product-moment correlations of the first and second testing sessions, and a two-way ANOVA (group between factor: NBI and BI and time within factor: session 1 and session 2) was performed on the summative scores to determine differences between each group.

Results: Test-retest reliability was strong and statistical significant for both the NBI ($r = .858, p = .014$) and the BI ($r = .967, p = .033$) groups. There was a significant difference between summative scores for the NBI and BI groups ($F_{1,20} = 42.325, p < .0001$).

Conclusion: The newly created Comprehensive Instrument for Evaluating Mild Traumatic Brain Injury (CIEMTBI) demonstrates good test-retest reliability and was able to discriminate the results between individuals in the NBI and BI groups. Further research, specifically with different samples, is needed to better determine the reliability and diagnostic accuracy of the instrument.

Level of Evidence: 2c

Key words: Balance, C3 Logix, Computerized, ImPACT, King Devick
INTRODUCTION
The diagnosis and treatment of an athlete who sustains a concussion, also known as a mild traumatic brain injury (mTBI), is presently one of the most controversial and poorly understood topics in sports medicine. Baseline testing is presently regarded as a key component in the standard for neurocognitive assessment following a suspected concussion. Current standard baseline testing is commonly performed using a computerized neurocognitive tool that assesses cognitive speed, processing, visual motor speed, and memory before and after distraction (both short and long term memory). A computerized assessment (i.e. ImPACT (ImPACT Applications, Inc. © 2016) or CCAT (Cogstate, LLC. 2011) is used at baseline and after injury as a tool for return to play evaluations. Progressive concussion treatment protocols for athletes include re-testing the concussed athlete with a computerized neurocognitive assessment after symptoms have resolved, comparing the results of the post-injury test to baseline test results, and progressing that athlete back into sport by gradually increasing physically demanding sport-specific activities. The neurocognitive assessment is typically performed on a computer and may not identify physical impairments (common sequelae of concussion) and may lack meaningful test-retest reliability. Neurocognitive testing, such as the ImPACT, may miss individuals attempting to manipulate test scores, supporting the inclusion of additional assessments in order to limit invalid outcomes.

New tests and methods are being developed and utilized to measure common physical deficits associated with concussions, and some tools have been shown to be reliable for identifying visual, vestibular, and balance dysfunction. These new assessment methods combined with aspects of computerized tools already utilized to assess cognitive function could assist athletic trainers and physicians in making return to play decisions, and help target treatments to areas of impairment. However, with so many methods for evaluating different aspects of concussion available, there may be confusion among health care providers regarding areas and severity of impairment. A unified tool that utilizes aspects of several different concussion-testing methods, and combining those methods into a single instrument, could help create a standard evaluation and guide patient care universally among health care providers.

The purpose of this study was to evaluate the test-retest reliability of a novel and comprehensive instrument for evaluating mild traumatic brain injury (referred to as “CIEMTBI”) that combines several currently utilized concussion assessment methods into one single, inclusive instrument that measures both neurocognitive function and physical capability. This newly developed instrument was evaluated for test-retest reliability within participants, and the results were compared between participants in two groups: one non-brain injured group in which participants have not sustained a brain injury and therefore should have normal neurocognitive function (NBI), and another brain injured group in which participants have sustained brain injury and should demonstrate impaired neurocognitive function (BI). The hypothesis is that the hybrid instrument will reliably identify both neurocognitive and physical impairments following a concussion, making it a reliable tool for assessing individuals who may have sustained a concussion.

METHODS
This research was designed as a pilot study to determine the test-retest reliability of a hybrid instrument created to detect impairments related to concussion/mTBI. The study was conducted on the campus of Northern Arizona University from September 2014 to March 2015. The protocol and design were submitted to the university institutional review board (IRB) and approved. During the course of the study, all procedures were in accordance with the ethic standard of the IRB. Participants were assigned a pseudo code identification number to maintain anonymity of study data and provided full disclosure prior to consent being attained.

Participants
Fourteen individuals (nine males, age: 29 ± 17.9, five females, age: 46.0 ± 21.5 years) participated in the study. Participants were recruited to volunteer for the study via referral from local healthcare providers. Furthermore, these participants met the inclusionary criteria of being capable of living independently, and either 1) having normal cognitive function without history of a negative health event...
(e.g. cerebral vascular accident/stroke, mTBI) that resulted in brain injury or cognitive impairment within one year of the study, or 2) having suffered a health event that has resulted in a medically documented impairment of cognitive function. Furthermore, those participants with impaired cognitive function were 14 days or more post-injury with persistent symptoms. Seven participants were assigned to the normal neurocognitive function, or non-brain-injured (NBI) group, and seven participants were assigned to the brain-injured (BI) group. Exclusionary criteria included history of concussion within one year of testing (for NBI participants only) and no symptoms of central vestibular pathology.

**Measures**

The CIEMTBI included the Dizziness Handicap Inventory (DHI), a symptom checklist incorporated with the C3 Logix system (developed by iComet Technologies in Cleveland, OH), a cognitive assessment battery that included challenges to immediate memory, concentration, language abilities, abstraction ability, coordination, delayed recall, balance (via C3 Logix), Vestibular/Ocular Motor Screening (VOMS), King-Devick test (manufactured by King-Devick Test in Oakbrook Terrace, IL), and the remainder of the C3 Logix system battery of tests, including ‘Trails A’ and ‘B’ along with processing speed assessments. All assessments will be described in detail later in this manuscript.

**Cognitive Assessment**

The cognitive assessment measured immediate memory by having the researcher read a list of five simple words to the participant. The participant was then given two trials to repeat the list of five words. The participant received one point for each word correctly remembered, and did not need to repeat words in the correct order. If the participant failed the first trial and could not repeat any words, a list of alternate words was used for the second trial.

**Concentration**

Concentration was assessed through challenges incorporating digit recall, attention, serial 7’s, and listing the months of the year in reverse order. Digit recall was similar to the immediate memory test, but it required the participant to repeat back a list of single digits read aloud by the researcher. First, the participant was asked to repeat a series of five digits in the same order as the researcher read, then the next four series of digits were repeated in the reverse order of what the researcher read. Each reverse order series increased the number of digits by one, from three to six digits. The attention assessment required the participant to tap their hand on a firm surface, which in this study was a desk, every time the researcher reads the letter “A” aloud in a series of other random letters. The participant was assigned zero points if they had no errors, or five points per error up to 10 points (two errors maximum). Serial 7’s required the participant to start at 99 and subtract by seven to countdown aloud to the number one. On repeated assessments participants were instructed to start at 98 or 99 to minimize learning effects. Participants received points for each number stated correctly. Finally, participants were asked to list aloud the months of the year in reverse order. No points were given if the participant did not make any errors, and 10 points were assigned if the participant made any errors. This was also timed.

**Language**

Language abilities were assessed by having the participant repeat sentences that were read aloud to them one time. One point was assigned for each correctly repeated sentence, with a maximum of six points possible. Abstraction was tested by requiring the participant to state the similarity between two words. Two points were assigned if the participant was able to correctly state a similarity, while the participant was given zero points if they could not correctly state a similarity. Examples might include listing an ‘orange’ and ‘apple’; the expected reply would have been ‘fruit’. Coordination was assessed only for the upper limbs, and was evaluated by having the participant move their finger (participant selected which arm to use) from their nose to as far in front of their nose as possible and back as quickly as they are able five times while fully extending the elbow and not missing the nose. After the coordination exam was complete, the participants were asked to repeat the five words that were read to them in the immediate memory section of the hybrid test. This was the delayed recall portion of the hybrid test. The participant received one point for each correctly recalled word.
C3 Logix Tests
The C3 Logix system is an iPad based application that has modules which assess for neurocognitive ability in several domains: symptomatology, reaction time, working memory and information processing, neuromotor function, balance, visual acuity, and vestibular function.22-27 The symptomatology was assessed at the beginning of the CIEMTBI with a graded symptom checklist that is comparable to the SCAT3. The symptom checklist on the iPad-based C3 Logix system was used instead of the SCAT3 form (which is filled in by the participant on paper) because it was more user friendly, particularly for some of the participants in the BI group with motor deficits and difficulty writing, and because it integrated well with the rest of the C3 Logix system. Balance was assessed approximately midway through the CIEMTBI via use of a belt that attached the iPad to the participant’s waist in order to measure sway using the Balance Error Scoring System (BESS). The balance assessment utilized the gyroscope and accelerometers in the iPad to detect quantifiable movement or sway (Figure 1). BESS procedures were followed according to standard protocol,23 with the participant only being tested on a firm surface (foam surface testing was not performed for safety of the BI group). Footwear was noted, with participants preferably only wearing socks, but not allowed to wear shoes, tape, or braces. The surface for balance testing was always hard conoleum tile, and the foot tested was always the participant’s non-dominant foot.

The remainder of the C3 Logix system test battery included assessments for processing speed, simple reaction time, choice reaction, and “Trails A and B”. Processing speed was assessed via a memory test that required association of symbols with numbers. Simple reaction time was measured by having the participant place their dominant hand index finger on a button that said “touch and hold” on the iPad screen below another yellow button on the iPad screen. The participant then had to move their finger from the touch and hold button to the yellow button as quickly as possible after the yellow button turned green. The choice reaction time test was similar to simple reaction, but it required both hands to be used, two yellow buttons were placed above two touch and hold buttons, and the participant had to move only the ipsilateral hand to the single yellow button that turned green. Trails A and B assessed neuromotor function by requiring the participant to draw a line between points that were either letters, numbers, or a mix of both, while also locating the numbers and/or letters in ascending sequence.

Vestibular/Ocular Motor Screening (VOMS)
The Vestibular/Ocular Motor Screening (VOMS) asked the participant to complete seven different head and eye movements, and rate their symptoms in four categories after each movement. These movements were: horizontal and vertical smooth pursuits, horizontal and vertical saccades, horizontal and vertical vestibuloocular reflex (VOR), and visual motion sensitivity. The researcher was positioned 10 feet away from the participant for all movements, and began all tests at the participant’s eye level directly in front of the participant’s eyes. Smooth pursuits
required the participant to move their eyes while keeping the head still as the researcher moved a finger between points three feet apart in horizontal and vertical planes. This sequence was completed twice in each plane. Saccades were performed by having the researcher hold up one finger on each hand three feet apart. The participant was then instructed to keep their head still and quickly move their eyes between the two fingers ten times in each vertical and horizontal plane. Vestibuloocular reflex was tested similarly to saccades, except the participant kept their eyes focused on a single point directly in front of their face 10 feet away and were instructed to move their head 45° in each direction (up and down for vertical plane, left and right for horizontal plane) 10 times at a 180 bpm pace. Visual motion sensitivity was tested by instructing the participant to hold a hand (self-selected) out with arm fully extended and thumb pointing up. The participant then kept their head still with eyes focused on the thumb, and rotated their body in the transverse plane 180° back and forth at a pace of 50 bpm five times.

**King-Devick test**

The King-Devick test was used as an assessment that tests for impairments in the following areas: saccades, attention, concentration, reading ability, and speech/language. This test requires the participant to read aloud a series of single digit numbers in order according to an established direction. The digits were printed on a card, and each series/card became increasingly more difficult via removal of the lines connecting the numbers, and then spacing the numbers closer together.

**Procedures**

Baseline evaluation data were collected for demographics, exclusionary criteria, and the hybrid instrument (which includes assessments designed to measure symptoms related to mTBI, cognitive skills related to memory, concentration, language abilities, abstraction ability, coordination, balance, visual acuity, and processing/reaction time). Participants were each assessed using the CIEMTBI instrument a total of two times: once at baseline, and once at a follow-up test within 72-96 hours of baseline testing to establish test re-test values. Each testing session took approximately 60 minutes. A table identifying each test used for the CIEMTBI can be seen in Table 1. No participants became ill during testing, and all follow-up testing was performed within 72-96 hours of baseline testing, as planned. However, some participants in the BI group were unable to complete certain sections of the CIEMTBI instrument due to inability (physical and/or cognitive) and/or refusal to attempt to complete the section. In that case, testing in that section of the instrument was stopped, a maximum score (most errors, or lowest performance rating) was assigned for that section, and the assessment continued until completion of the instrument. In a post-concussion setting, this practice would allow the score to demonstrate improvement during recovery; and it is expected that some patients immediately post mTBI might have difficulty completing all of the involved tasks.

**Statistical Analyses**

**Creation of a Summative Score**

All variables were recoded to be on a 10-point scale to prevent one item from being more influential over others. These subscales were then added together to create a summative score.
create 11 different variables that were then summed together, creating one summative value for each testing session. These 11 variables included: DHI, Symptoms, Cognition, Language, Abstract, Coordination, Delayed Recall, Balance, VOMS, King-Devick and Processing Speed. Placing each of the 11 subscales on a 10-point scale allowed for the summative score to range from 0-110. The lower the summative score the less cognitively impaired the individual. If necessary, subscale values were reversed to assign lower scores to indicate fewer errors the participant made per variable.

**Test-retest reliability**

Test-retest reliability was measured using Pearson product-moment correlations of the first and second administration of the test, specifically the summative score of each testing session. Also, one paired t-test was performed on the summative scores within each group (NBI and BI) to ensure that the within group variance was stable between the first and second testing sessions. A two-way ANOVA was conducted using testing session as the within participants variable (session 1 and session 2) and group membership as the between participants variable (NBI and BI). The following averages of time were created for comparisons (Serial 7s/Months in Reverse Order, Trails A/B, Simple/Choice Reaction Times, and King-Devick average time). A two-way ANOVA was performed on the four continuous time dependent variables with the within participants variable (session 1 and session 2) and the between participants variable (NBI and BI). All analyses were performed using Statistical Package for the Social Sciences (SPSS, version 21) with alpha set to p<0.05.

**RESULTS**

The test-retest reliability was strong for both the NBI ($r = .858, p = .014$) and the BI ($r = .967, p = .033$) groups showing that the outcomes were repeatable and stable between testing sessions. There were also no differences seen between the means, as an entire sample, from testing session 1 to session 2 ($t_{10} = .001, p = 1.000$). There was a significant difference between the NBI and BI groups on the summative scores ($F_{1,20} = 42.325, p < .0001$), suggesting that the instrument is able to detect differences between neurocognitive impairment or functional limitations and normal neurocognitive function. The average summative score for the NBI participants (12.65 ± 4.75) was nearly 23 points lower than that of the participants in the BI group (35.71 ± 11.66). Furthermore, there was no interaction between group membership and testing session ($F_{1,20} = .602, p = .447$). For all of the comparisons on the time variables the NBI participants were significantly faster (Serial 7s/Months in Reverse Order: $F_{1,20} = 5.990, p = .024$; Trails A/B: $F_{1,17} = 7.917, p = .012$; Simple/Choice Reaction Times: $F_{1,20} = 20.946, p < .0001$; and King Devick average time: $F_{1,19} = 37.667, p < .0001$).

**DISCUSSION**

The researchers evaluated the test-retest reliability of a newly created instrument, the CIEMTBI, that measures both neurocognitive function and physical capability. Reliability was assessed by comparing testing results within participants and between participants in two different groups. These two groups - one with normal neurocognitive function and one with impaired neurocognitive function - were compared in order to demonstrate that the testing scores remained consistent within participants, but varied between groups. This suggests that the CIEMTBI instrument was reliable with repeated testing sessions, and it was also able to detect differences between neurocognitive impairment or functional limitations and normal neurocognitive function. Thus, with further replications, this instrument may be able to detect a change in an athlete’s mental and physical status before and after sustaining a concussion.

The CIEMTBI instrument combines several currently utilized concussion assessment methods into a single tool, and the reliability of the instrument as a whole ($r = .858$ in the NBI group, $r = .967$ in the BI group) was similar to or higher than the reliability of each individual component. The Dizziness Handicap Inventory has been reported to have test-retest reliability of $r = .97$. The hybrid instrument also utilizes several components of the Standardized Assessment of Concussion (SAC) and the Montreal Cognitive Assessment (MoCA). Barr and McCrea reported moderate test-retest reliability for the SAC ($r = .55$), and Nasreddine et al. reported strong test-retest reliability for the MoCA ($r = .92$).

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The mean age of the NBI group (25.0 ± 2.3) was much lower than that of the BI group (47.8 ± 25.6). This could potentially lead to a greater difference between groups on the summative scores due to typical decreases in neurocognitive function due, in part, to normal aging. Furthermore, this study had a low sample size. Although this was a pilot study and was designed considering a low sample size, not having a large enough sample could potentially affect the results. A final limitation of this work could be the cost of the C3 Logix system (~$1,800.00), which requires the use of an iPad as well.

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The results from this study suggest that the CIEMTBI may be a viable option for sports medicine teams to use in the evaluation of athletes who may have sustained a concussion, although its use does not need to be limited to athletics. This could also apply to other individuals at risk of mTBI/concussion, such as military personnel. Furthermore, because the effects of concussion vary between individuals, this instrument may be a valuable tool that can be used as a standard measure of concussion impairment. Since there are many other tools available to assess different aspects of impairment that may be due to concussion, health care providers may not be using the same evaluation methods, which could potentially cause confusion. A unified, single tool, such as the CIEMTBI, could help create a standard evaluation of concussion, and can help guide plan of care on a universal level.

Further research is needed to examine the reliability of this instrument with a larger sample size of both brain-injured and healthy participants. The CIEMTBI should also be studied to evaluate its diagnostic accuracy for detecting impairments related to concussion. Although the results from this study provide data that suggests the hybrid instrument is able to detect differences between neurocognitive impairment or functional limitations and normal neurocognitive function, and it showed significant differences in time and balance variables between the BI and NBI groups.

Limitations

One limitation of this study is that the researchers did not have detailed medical records or medical histories for our participants. Only the participants’ medical history that was relevant to the study (i.e., history of brain injury or head trauma, having been diagnosed with ADD/ADHD, etc.) was collected, and all medical history was self-reported by the participants without documentation to verify participant reports. Another potential limitation of the study is that the mean age of the NBI group (25.0 ± 2.3) was much lower than that of the BI group (47.8 ± 25.6). This could potentially lead to a greater difference between groups on the summative scores due to typical decreases in neurocognitive function due, in part, to normal aging. Furthermore, this study had a low sample size. Although this was a pilot study and was designed considering a low sample size, not having a large enough sample could potentially affect the results. A final limitation of this work could be the cost of the C3 Logix system (~$1,800.00), which requires the use of an iPad as well.

CONCLUSION

Baseline and post-injury testing is currently part of the standard of care in concussion management. It was found that the CIEMTBI, which combines sev-
eral aspects of concussion assessment and challenges both neurocognitive and physical abilities, has good test-retest reliability, and also may be able to detect differences between neurocognitive impairment and normal neurocognitive function. This may be a valuable tool for clinicians involved in concussion assessment and return to play decisions. Further research is needed to better determine the reliability and diagnostic accuracy of the instrument.

REFERENCES


ABSTRACT

Background: One common component of concussion rehabilitation is a computerized cognitive test free of concomitant physical demands. Healthcare professionals may be able to provide more patient-centered care after a diagnosed concussion if specific areas of impairment are identified and treated, such as the physical aspect of neurocognitive function.

Hypothesis/Purpose: To evaluate the test-retest reliability of a unique combination of neurocognitive assessment tools currently utilized in concussion assessments into one single, inclusive instrument that measures both neurocognitive function and physical capability.

Study Design: Original research – diagnostic tests.

Methods: Fourteen individuals (nine males, age: 29 ± 17.9, five females, age: 46.0 ± 21.5 years) either with normal cognitive function (NBI) without history of a health event (e.g. cerebral vascular accident/stroke, mTBI) that resulted in brain injury within one year of the study, or who had suffered a health event that has resulted in a medically documented brain injury (BI) participated in the study. Participants completed the full hybrid assessment instrument for a baseline test, then completed a follow-up test using the same instrument within 72-96 hours of baseline. Test-retest reliability was measured using Pearson product-moment correlations of the first and second testing sessions, and a two-way ANOVA (group between factor: NBI and BI and time within factor: session 1 and session 2) was performed on the summative scores to determine differences between each group.

Results: Test-retest reliability was strong and statistical significant for both the NBI (r = .858, p = .014) and the BI (r = .967, p = .033) groups. There was a significant difference between summative scores for the NBI and BI groups (F1,20 = 42.325, p < .0001).

Conclusion: The newly created Comprehensive Instrument for Evaluating Mild Traumatic Brain Injury (CIEMTBI) demonstrates good test-retest reliability and was able to discriminate the results between individuals in the NBI and BI groups. Further research, specifically with different samples, is needed to better determine the reliability and diagnostic accuracy of the instrument.

Level of Evidence: 2c

Key words: Balance, C3 Logix, Computerized, ImPACT, King Devick
INTRODUCTION
The diagnosis and treatment of an athlete who sustains a concussion, also known as a mild traumatic brain injury (mTBI), is presently one of the most controversial and poorly understood topics in sports medicine.1-4 Baseline testing is presently regarded as a key component in the standard for neurocognitive assessment following a suspected concussion.5 Current standard baseline testing is commonly performed using a computerized neurocognitive tool that assesses cognitive speed, processing, visual motor speed, and memory before and after distraction (both short and long term memory).6 A computerized assessment (i.e. ImPACT (ImPACT Applications, Inc. © 2016) or CGAT (Cogstate, LLC. 2011) is used at baseline and after injury as a tool for return to play evaluations.6,7 Progressive concussion treatment protocols for athletes include re-testing the concussed athlete with a computerized neurocognitive assessment after symptoms have resolved, comparing the results of the post-injury test to baseline test results, and progressing that athlete back into sport by gradually increasing physically demanding sport-specific activities.8-10 The neurocognitive assessment is typically performed on a computer and may not identify physical impairments (common sequelae of concussion) and may lack meaningful test-retest reliability.6,7 Neurocognitive testing, such as the ImPACT, may miss individuals attempting to manipulate test scores, supporting the inclusion of additional assessments in order to limit invalid outcomes.11
New tests and methods are being developed and utilized to measure common physical deficits associated with concussions, and some tools have been shown to be reliable for identifying visual, vestibular, and balance dysfunction.12-16 These new assessment methods combined with aspects of computerized tools already utilized to assess cognitive function could assist athletic trainers and physicians in making return to play decisions, and help target treatments to areas of impairment. However, with so many methods for evaluating different aspects of concussion available, there may be confusion among health care providers regarding areas and severity of impairment. A unified tool that utilizes aspects of several different concussion-testing methods, and combining those methods into a single instrument, could help create a standard evaluation and guide patient care universally among health care providers.

The purpose of this study was to evaluate the test-retest reliability of a novel and comprehensive instrument for evaluating mild traumatic brain injury (referred to as “CIEMTBI”) that combines several currently utilized concussion assessment methods8,13,15-27 into one single, inclusive instrument that measures both neurocognitive function and physical capability. This newly developed instrument was evaluated for test-retest reliability within participants, and the results were compared between participants in two groups: one non-brain injured group in which participants have not sustained a brain injury and therefore should have normal neurocognitive function (NBI), and another brain injured group in which participants have sustained brain injury and should demonstrate impaired neurocognitive function (BI). The hypothesis is that the hybrid instrument will reliably identify both neurocognitive and physical impairments following a concussion, making it a reliable tool for assessing individuals who may have sustained a concussion.

METHODS
This research was designed as a pilot study to determine the test-retest reliability of a hybrid instrument created to detect impairments related to concussion/mTBI. The study was conducted on the campus of Northern Arizona University from September 2014 to March 2015. The protocol and design were submitted to the university institutional review board (IRB) and approved. During the course of the study, all procedures were in accordance with the ethic standard of the IRB. Participants were assigned a pseudo code identification number to maintain anonymity of study data and provided full disclosure prior to consent being attained.

Participants
Fourteen individuals (nine males, age: 29 ± 17.9, five females, age: 46.0 ± 21.5 years) participated in the study. Participants were recruited to volunteer for the study via referral from local healthcare providers. Furthermore, these participants met the inclusionary criteria of being capable of living independently, and either 1) having normal cognitive function without history of a negative health event
(e.g. cerebral vascular accident/stroke, mTBI) that resulted in brain injury or cognitive impairment within one year of the study, or 2) having suffered a health event that has resulted in a medically documented impairment of cognitive function. Furthermore, those participants with impaired cognitive function were 14 days or more post-injury with persistent symptoms. Seven participants were assigned to the normal neurocognitive function, or non-brain-injured (NBI) group, and seven participants were assigned to the brain-injured (BI) group. Exclusionary criteria included history of concussion within one year of testing (for NBI participants only) and no symptoms of central vestibular pathology.

**Measures**

The CIEMTBI included the Dizziness Handicap Inventory (DHI), a symptom checklist incorporated with the C3 Logix system (developed by iComet Technologies in Cleveland, OH), a cognitive assessment battery that included challenges to immediate memory, concentration, language abilities, abstraction ability, coordination, delayed recall, balance (via C3 Logix), Vestibular/Ocular Motor Screening (VOMS), King-Devick test (manufactured by King-Devick Test in Oakbrook Terrace, IL), and the remainder of the C3 Logix system battery of tests, including Trails ‘A’ and ‘B’ along with processing speed assessments. All assessments will be described in detail later in this manuscript.

**Cognitive Assessment**

The cognitive assessment measured immediate memory by having the researcher read a list of five simple words to the participant. The participant was then given two trials to repeat the list of five words. The participant received one point for each word correctly remembered, and did not need to repeat words in the correct order. If the participant failed the first trial and could not repeat any words, a list of alternate words was used for the second trial.

**Concentration**

Concentration was assessed through challenges incorporating digit recall, attention, serial 7’s, and listing the months of the year in reverse order. Digit recall was similar to the immediate memory test, but it required the participant to repeat back a list of single digits read aloud by the researcher. First, the participant was asked to repeat a series of five digits in the same order as the researcher read, then the next four series of digits were repeated in the reverse order of what the researcher read. Each reverse order series increased the number of digits by one, from three to six digits. The attention assessment required the participant to tap their hand on a firm surface, which in this study was a desk, every time the researcher reads the letter “A” aloud in a series of other random letters. The participant was assigned zero points if they had no errors, or five points per error up to 10 points (two errors maximum). Serial 7’s required the participant to start at 99 and subtract by seven to countdown aloud to the number one. On repeated assessments participants were instructed to start at 98 or 99 to minimize learning effects. Participants received points for each number stated correctly. Finally, participants were asked to list aloud the months of the year in reverse order. No points were given if the participant did not make any errors, and 10 points were assigned if the participant made any errors. This was also timed.

**Language**

Language abilities were assessed by having the participant repeat sentences that were read aloud to them one time. One point was assigned for each correctly repeated sentence, with a maximum of six points possible. Abstraction was tested by requiring the participant to state the similarity between two words. Two points were assigned if the participant was able to correctly state a similarity, while the participant was given zero points if they could not correctly state a similarity. Examples might include listing an ‘orange’ and ‘apple’; the expected reply would have been ‘fruit’. Coordination was assessed only for the upper limbs, and was evaluated by having the participant move their finger (participant selected which arm to use) from their nose to as far in front of their nose as possible and back as quickly as they are able five times while fully extending the elbow and not missing the nose. After the coordination exam was complete, the participants were asked to repeat the five words that were read to them in the immediate memory section of the hybrid test. This was the delayed recall portion of the hybrid test. The participant received one point for each correctly recalled word.
**C3 Logix Tests**

The C3 Logix system is an iPad based application that has modules which assess for neurocognitive ability in several domains: symptomatology, reaction time, working memory and information processing, neuromotor function, balance, visual acuity, and vestibular function.\(^{22-27}\) The symptomatology was assessed at the beginning of the CIEMTBI with a graded symptom checklist that is comparable to the SCAT3. The symptom checklist on the iPad-based C3 Logix system was used instead of the SCAT3 form (which is filled in by the participant on paper) because it was more user friendly, particularly for some of the participants in the BI group with motor deficits and difficulty writing, and because it integrated well with the rest of the C3 Logix system. Balance was assessed approximately midway through the CIEMTBI via use of a belt that attached the iPad to the participant’s waist in order to measure sway using the Balance Error Scoring System (BESS). The balance assessment utilized the gyroscope and accelerometers in the iPad to detect quantifiable movement or sway (Figure 1). BESS procedures were followed according to standard protocol,\(^{23}\) with the participant only being tested on a firm surface (foam surface testing was not performed for safety of the BI group). Footwear was noted, with participants preferably only wearing socks, but not allowed to wear shoes, tape, or braces. The surface for balance testing was always hard congoleum tile, and the foot tested was always the participant’s non-dominant foot.

The remainder of the C3 Logix system test battery included assessments for processing speed, simple reaction time, choice reaction, and “Trails A and B”. Processing speed was assessed via a memory test that required association of symbols with numbers. Simple reaction time was measured by having the participant place their dominant hand index finger on a button that said “touch and hold” on the iPad screen below another yellow button on the iPad screen. The participant then had to move their finger from the touch and hold button to the yellow button as quickly as possible after the yellow button turned green. The choice reaction time test was similar to simple reaction, but it required both hands to be used, two yellow buttons were placed above two touch and hold buttons, and the participant had to move only the ipsilateral hand to the single yellow button that turned green. Trails A and B assessed neuromotor function by requiring the participant to draw a line between points that were either letters, numbers, or a mix of both, while also locating the numbers and/or letters in ascending sequence.

**Vestibular/Ocular Motor Screening (VOMS)**

The Vestibular/Ocular Motor Screening (VOMS) asked the participant to complete seven different head and eye movements, and rate their symptoms in four categories after each movement. These movements were: horizontal and vertical smooth pursuits, horizontal and vertical saccades, horizontal and vertical vestibuloocular reflex (VOR), and visual motion sensitivity. The researcher was positioned 10 feet away from the participant for all movements, and began all tests at the participant’s eye level directly in front of the participant’s eyes. Smooth pursuits...
required the participant to move their eyes while keeping the head still as the researcher moved a finger between points three feet apart in horizontal and vertical planes. This sequence was completed twice in each plane. Saccades were performed by having the researcher hold up one finger on each hand three feet apart. The participant was then instructed to keep their head still and quickly move their eyes between the two fingers ten times in each vertical and horizontal plane. Vestibuloocular reflex was tested similarly to saccades, except the participant kept their eyes focused on a single point directly in front of their face 10 feet away and were instructed to move their head 45° in each direction (up and down for vertical plane, left and right for horizontal plane) 10 times at a 180 bpm pace. Visual motion sensitivity was tested by instructing the participant to hold a hand (self-selected) out with arm fully extended and thumb pointing up. The participant then kept their head still with eyes focused on the thumb, and rotated their body in the transverse plane 180° back and forth at a pace of 50 bpm five times.

**King-Devick test**

The King-Devick test was used as an assessment that tests for impairments in the following areas: saccades, attention, concentration, reading ability, and speech/language.19 This test requires the participant to read aloud a series of single digit numbers in order according to an established direction. The digits were printed on a card, and each series/card became increasingly more difficult via removal of the lines connecting the numbers, and then spacing the numbers closer together.

**Procedures**

Baseline evaluation data were collected for demographics, exclusionary criteria, and the hybrid instrument (which includes assessments designed to measure symptoms related to mTBI, cognitive skills related to memory, concentration, language abilities, abstraction ability, coordination, balance, visual acuity, and processing/reaction time). Participants were each assessed using the CIEMTBI instrument a total of two times: once at baseline, and once at a follow-up test within 72-96 hours of baseline testing to establish test re-test values. Each testing session took approximately 60 minutes. A table identifying each test used for the CIEMTBI can be seen in Table 1. No participants became ill during testing, and all follow-up testing was performed within 72-96 hours of baseline testing, as planned. However, some participants in the BI group were unable to complete certain sections of the CIEMTBI instrument due to inability (physical and/or cognitive) and/or refusal to attempt to complete the section. In that case, testing in that section of the instrument was stopped, a maximum score (most errors, or lowest performance rating) was assigned for that section, and the assessment continued until completion of the instrument. In a post-concussion setting, this practice would allow the score to demonstrate improvement during recovery; and it is expected that some patients immediately post mTBI might have difficulty completing all of the involved tasks.

**Statistical Analyses**

**Creation of a Summative Score**

All variables were recoded to be on a 10-point scale to prevent one item from being more influential over others. These subscales were then added together to

<table>
<thead>
<tr>
<th>Table 1. Individual Tests of Comprehensive Instrument for Evaluating Mild Traumatic Brain Injury (CIEMTBI)</th>
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<tbody>
<tr>
<td>Dizziness Handicap Inventory</td>
</tr>
<tr>
<td>Symptom Checklist38</td>
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<tr>
<td>Cognitive Assessment Battery of Tests:</td>
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<tr>
<td>Immediate memory39,40</td>
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Kontos et al. reported high internal consistency for the VOMS (Cronbach $\alpha = .97$). The Kontos et al
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study was not able to report test-retest reliability data because only time points from a single evaluation were available for statistical analysis. Although the instrument test-retest reliability findings of this study cannot be directly compared to the internal consistency findings of Kontos et al, the high internal consistency of the VOMS supports its inclusion in the hybrid instrument, and it is not likely that the VOMS as a subscale of the instrument reduced the reliability of the CIEMTBI instrument. Further research is warranted to determine the test-retest reliability of the newly developed VOMS.

Furthermore, Galetta et al.32 found strong test-retest reliability for the King-Devick test (ICC = .97). Bell et al.23 reported adequate reliability for the BESS test (ICC = .70). Serial 7s has also been shown to have reliability similar to that of our CIEMTBI instrument, which also utilizes serial 7s (serial 7s r = .7-.81, hybrid instrument r = .858 in the NBI group, r = .967 in the BI group).33,34 Moreover, the reliability of the CIEMTBI instrument (r = .858 - .967) was found to be higher than previous studies found using intraclass correlation coefficients (ICC) for the ImPACT test (ICC < .75)6 or for the Axon Sports Computerized Cognitive Assessment Tool (ICC = .401 - .672).7 Although the reported findings of this study cannot be definitively compared to the ICC values previously found for other tests, the present findings support the need for further research to perform ICC analysis of the CIEMTBI instrument. Additionally, our study supports previous work that indicates comprehensive concussion assessment should be multifaceted4,6,9,13,35 because the CIEMTBI was able to detect differences between neurocognitive impairment or functional limitations and normal neurocognitive function, and it showed significant differences in time and balance variables between the BI and NBI groups.

Limitations
One limitation of this study is that the researchers did not have detailed medical records or medical histories for our participants. Only the participants' medical history that was relevant to the study (i.e. history of brain injury or head trauma, having been diagnosed with ADD/ADHD, etc.) was collected, and all medical history was self-reported by the participants without documentation to verify participant reports. Another potential limitation of the study is that the mean age of the NBI group (25.0 ± 2.3) was much lower than that of the BI group (47.8 ± 25.6). This could potentially lead to a greater difference between groups on the summative scores due to typical decreases in neurocognitive function due, in part, to normal aging.36,37 Furthermore, this study had a low sample size. Although this was a pilot study and was designed considering a low sample size, not having a large enough sample could potentially affect the results. A final limitation of this work could be the cost of the C3 Logix system (~$1,800.00), which requires the use of an iPad as well.

Clinical Relevance
The results from this study suggest that the CIEMTBI may be a viable option for sports medicine teams to use in the evaluation of athletes who may have sustained a concussion, although its use does not need to be limited to athletics. This could also apply to other individuals at risk of mTBI/concussion, such as military personnel.5 Furthermore, because the effects of concussion vary between individuals, this instrument may be a valuable tool that can be used as a standard measure of concussion impairment. Since there are many other tools available to assess different aspects of impairment that may be due to concussion, health care providers may not be using the same evaluation methods, which could potentially cause confusion. A unified, single tool, such as the CIEMTBI, could help create a standard evaluation of concussion, and can help guide plan of care on a universal level.

Further research is needed to examine the reliability of this instrument with a larger sample size of both brain-injured and healthy participants. The CIEMTBI should also be studied to evaluate its diagnostic accuracy for detecting impairments related to concussion. Although the results from this study provide data that suggests the hybrid instrument is able to detect differences between neurocognitive impairment or functional limitations and normal neurocognitive function, a validation study would allow for determination of the exact impairments the hybrid instrument can detect, and with what accuracy.

CONCLUSION
Baseline and post-injury testing is currently part of the standard of care in concussion management. It was found that the CIEMTBI, which combines sev-
eral aspects of assessment concussion and challenges both neurocognitive and physical abilities, has good test-retest reliability, and also may be able to detect differences between neurocognitive impairment and normal neurocognitive function. This may be a valuable tool for clinicians involved in concussion assessment and return to play decisions. Further research is needed to better determine the reliability and diagnostic accuracy of the instrument.

REFERENCES


ABSTRACT

Background: Muscular weakness of the shoulder complex is commonly found in patients presenting with scapular dyskinesis; however, little is known regarding muscular performance in healthy individuals with scapular dyskinesis.

Purpose: To compare isometric strength measures of the shoulder complex between healthy individuals with and without scapular dyskinesis. It was hypothesized that healthy individuals with scapular dyskinesis would demonstrate decreased isometric strength of the scapular stabilizers and rotator cuff when compared to healthy individuals without scapular dyskinesis.

Study Design: Cross-sectional study.

Methods: Forty healthy, college-aged participants were recruited. Sixty-eight percent of subjects (27 of 40) presented with scapular dyskinesis. Thus, a matched-pairs analysis was conducted with 26 subjects (age: 22.00 ± 2.06 y; height: 168.77 ± 8.07 cm; mass: 70.98 ± 13.14 kg; BMI: 24.75 ± 3.04 kg/m²; 6 males; 20 females). The presence of scapular dyskinesis was determined visually using the scapular dyskinesis test with a dichotomous outcome (yes/no). Strength of the scapular stabilizers and rotator cuff was assessed via manual muscle testing using a handheld dynamometer. Force measures obtained with the handheld dynamometer were used to quantify strength. For each muscle tested, the mean peak force of three trials were normalized to body weight and used for data analysis. Additionally, strength ratios were calculated and analyzed. Differences in strength and strength ratios between those with and without scapular dyskinesis were compared using separate two-way mixed ANOVAs with repeated measures.

Results: No significant differences for either strength (F(1, 31, 43.92) = 1.10, p = .34) or strength ratios (F(1, 31, 44.02) = 1.93, p = .16) were observed between those with and without scapular dyskinesis. A significant main effect (F(1, 31, 43.92) = 239.32, p < .01) for muscles tested was observed, and post-hoc analysis revealed significant trends resulting in a generalized order: the upper trapezius generated the greatest amount of force, followed by serratus anterior and middle trapezius, lower trapezius, supraspinatus, medial rotators, and lateral rotators.

Conclusion: The results of this study indicate that differences in shoulder muscle strength do not exist between healthy subjects with and without scapular dyskinesis. Additionally, scapular dyskinesis appears to be prevalent in healthy populations.

Level of Evidence: Level 3

Key words: Muscular performance, rotator cuff, scapular dysfunction, scapular stabilizers, shoulder

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INTRODUCTION
Musculoskeletal disorders of the shoulder complex are common among the general population and those who participate in overhead sports. Incidence rates for shoulder pain in the general population are between 0.9 – 2.5% with a lifetime prevalence between 6.7-66.7%. The frequency of shoulder pain is much higher in those individuals participating in overhead sports. As such, the socioeconomic impact can be quite substantial. In fact, direct health care expenditures associated with treatment of shoulder dysfunction in the year 2000 totaled $7 billion. The occurrence of shoulder pain has been linked to scapular dysfunction. Scapular dyskinesis is used to describe aberrant movement patterns of the scapula, which may serve as a potential source of impairment to normal shoulder function. It is common to find scapular dyskinesis associated with a variety of shoulder pathologies including, but not limited to, impingement, rotator cuff tears, labral pathology, acromioclavicular separations, and multidirectional instability of the glenohumeral joint. However, it is increasingly apparent that scapular dyskinesis exists in healthy populations as well. Therefore, the question remains as to whether scapular dyskinesis predisposes an individual to injury. Unfortunately, conflicting evidence exists among prospective studies regarding whether scapular dyskinesis is a causative factor for upper extremity injury.

While the amount of research on the role of the scapula continues to increase, the exact cause for the development of scapular dyskinesis is not fully understood. There are several probable causes including, bony pathology (e.g., clavicular fracture), joint pathology (e.g., acromioclavicular separation), neurological pathology (e.g., long thoracic nerve palsy), soft tissue inflexibility (e.g., pectoralis minor tightness), and decreased muscle performance (e.g., altered activation patterns or strength deficits). Decreased muscle performance of the scapulothoracic musculature has been linked to altered shoulder kinematics, which may predispose an individual to injury. Thus, rehabilitation programs have been suggested to focus on improving the performance of the rotator cuff and scapular stabilizers.

Clinicians may benefit from collecting shoulder strength data to better identify those with scapular dyskinesis who would benefit from a rehabilitation program focused on improving muscle performance. These data can easily be collected with a handheld dynamometer given that it is cost-effective, reliable, and valid. Normative strength data, including antagonist ratios, exists for the rotator cuff and scapular stabilizers in healthy populations. Others have reported strength profiles of the shoulder in healthy overhead athletes. While these studies included only healthy participants, none of these studies controlled for the presence of scapular dyskinesis. Those studies that have controlled for scapular dyskinesis have revealed rotator cuff weakness. However, it is important to note that these studies delimited the scapular dyskinesis groups with only symptomatic participants. In addition, authors have speculated that weakness of the scapular stabilizers exists in those with scapular dyskinesis based on studies examining electromyographic activity, or comparing strength data in those with and without shoulder impingement. Currently, only one study has directly compared strength measures between groups with and without scapular dyskinesis in a population of asymptomatic overhead athletes. While significant weakness of the lower trapezius was demonstrated in the scapular dyskinesis group, the authors limited their strength measurements to only the lower trapezius and serratus anterior. Additional studies are needed that examine strength data of the scapular stabilizers and rotator cuff to gain a better understanding of the clinical relevance of scapular dyskinesis, as well as providing additional means to diagnose, monitor, and measure patient outcomes during the rehabilitation process. Therefore, the primary aim of this study was to compare strength measures of the shoulder complex between healthy individuals with and without scapular dyskinesis.

METHODS
Participants
A convenience sample of 40 participants volunteered to participate in the study (age = 22.2 ± 2.4 years; height = 169.9 ± 8.7 cm; mass = 68.7 ± 13.0 kg; body mass index (BMI) = 23.7 ± 3.1 kg/m²; sex
Participants were recruited from the School of Health Sciences at Duquesne University. All participants were included that met the following inclusion criteria: 1) between the ages of 18 and 40, and 2) no history of neck or dominant shoulder injury or pathology. Shoulder dominance was determined by which arm the participant would use to throw a ball. Exclusion criteria included 1) the presence of any neurological condition that affected muscular strength and consequent upper extremity range of motion, 2) inability to achieve ≥ 140° of shoulder elevation, 3) any previous surgery on the dominant shoulder, 4) diagnosis of rheumatoid arthritis, and 5) if the participant was currently pregnant. The University's institutional review board approved the study and all participants were required to provide written informed consent prior to participation.

To ensure adequate statistical power, a power analysis was performed using G*Power 3.1.9.2. Based on preliminary data from 10 subjects, an effect size was calculated ($f = .313$), and operating at a power of 80% and $\alpha = .05$, it was determined that an estimated sample size of 22 participants was needed to detect significant differences in strength. While collecting data, an apparent disparity was revealed in the number of participants with and without scapular dyskinesis. Scapular dyskinesis, as defined by the methods described in this study, was observed in 68% (10/13 males, 17/27 females) of the participants. Therefore, a matched-pairs analysis was utilized, which yielded 13 matched-pairs from the sample. (Table 1) The participants were matched according to sex and BMI. The remaining 14 participants from the sample were excluded from the study because suitable pairings were unavailable.

### Procedures
All participants completed the Physical Activity Readiness Questionnaire (PAR-Q) to establish general health fitness. If participants checked “yes” for any of the listed items they were disqualified from the study. To confirm a healthy shoulder status, all participants completed the patient self-report section and underwent the physical examination section of the American Shoulder and Elbow Surgeons Standardized Shoulder Assessment (ASES). Any presence of decreased range of motion, strength, or other clinical findings that suggested shoulder pathology upon examination would have resulted in exclusion from the study.

#### Scapular Dyskinesis Test
Participants were evaluated for scapular dysfunction of the dominant shoulder utilizing the scapular dyskinesis test. The participants performed separate trials of bilateral shoulder flexion and abduction while holding either a 1.4 kg or 2.3 kg weight: 1.4 kg for body masses < 68.1 kg and 2.3 kg for body masses > 68.1 kg. The test was modified by having the participants perform 10 repetitions for each movement. Movement velocity was standardized across all participants by way of a metronome set at 80 beats per minute resulting in a movement velocity of approximately 120°/s; therefore, each trial lasted 30 seconds. Performance of the test was digitally recorded from a standardized distance and height for documentation purposes.

The presence of scapular dyskinesis was determined by scapular winging, dysrhythmia, or both as defined by McClure et al. Scapular winging was defined as any posterior displacement of the medial border and/or inferior angle of the scapula away from the thorax. Dysrhythmia was defined as any early or excessive elevation or protraction, non-rhythmic motion while raising or lowering the arm, or rapid downward rotation while lowering the arm. A dichotomous method (yes/no) was used to categorize those with and without scapular dyskinesis. One investigator, with 14 years of clinical experience as an athletic trainer, evaluated all participants and determined the presence of scapular dyskinesis. Test-retest reliability (coefficient of agreement = .99) was assessed using digital recordings of 10 subjects that were randomly chosen from the sample. Reassessment occurred within a period of 48 hours. The investigator was blinded to the original scoring, and subject ordering was randomized to decrease bias.

#### Manual Muscle Tests
Participants underwent eight manual muscle tests of muscles around the shoulder complex: upper trapezius (two methods), middle trapezius, lower trapezius, serratus anterior, supraspinatus, and the medial and lateral rotators of the humerus. The
order of the strength tests were randomized. A hand-held dynamometer (ergoFET 300, Hogan Health Industries®, West Jordon, UT), with a manufacturer’s reported accuracy of +/- 2%, was used to assess the peak force (N) exerted during the tests. Measures of force captured by the handheld dynamometer during the manual muscle tests were used to quantify measures of strength. Prior to data collection, the dynamometer was assessed for accuracy by comparing known loads applied to the dynamometer and its recorded values ($r = .9998$). For each muscle test, the participants were asked to generate a maximal effort against the resistance being applied by the investigator. Thus, participants performed a “make test” rather than a “break test” as it is commonly used in handheld dynamometry studies.24-28 Participants were asked to gradually build up their effort over a two-second period and maintain a maximum effort for three seconds. Three trials were performed for each manual muscle test with a 30-second rest period between each trial, and approximately one minute of rest between each muscle. Prior to performing the manual muscle tests, participants were provided instruction on proper performance of the test. Additionally, participants performed two to three sub-maximal efforts in order to become accustomed to the testing procedures.

Two different methods were used to evaluate the upper trapezius. The first method (UT1) was performed as described by Hislop et al39 (Figure 1). The participant was seated with the hands resting on the thighs, and the shoulder girdle was positioned at the midrange of elevation. The dynamometer was placed on the acromion process and the resistance was directed inferiorly. The second method (UT2) was performed with the participant standing atop of a modified rake handle while grasping the dynamometer with the dominant hand (Figure 2). For this test, the manufacturer’s handle and hook accessories were affixed to the dynamometer. The dynamometer was attached to the modified rake handle by a metal chain. A screen was placed immediately adjacent to the participant on the non-dominant side to aide in limiting extraneous lateral trunk motion. The dynamometer was affixed to the chain at a height that positioned the participant’s shoulder girdle in the midrange of elevation. The participant was instructed to shrug their shoulder superiorly, while maintaining an extended elbow, against the resistance.

The serratus anterior (SA) was tested as described by Kendall et al40 (Figure 3). The participant was seated with the dominant arm positioned in 120° of shoulder flexion with the thumb pointed in an upward direction. The dynamometer was positioned on the humerus at the level of the deltoid insertion, and the resistance was applied in a downward direction that was perpendicular to the humerus.

Strength of the middle trapezius (MT) was measured as described by Kendall et al40 (Figure 4). The participant was positioned prone on a plinth with the shoulder abducted to 90° and the humerus laterally rotated where the thumb pointed toward the ceil-
ing. The location of the resistance force applied by the tester was modified whereby the dynamometer was positioned on the spine of the scapula approximately 2/3 of the distance from the root of the spine to the posterolateral angle of the acromion. The position was modified in an effort to isolate the measured forces to the scapulothoracic musculature and prevent the involvement of other muscular forces (e.g., rotator cuff). The resistance was applied in an anterolateral direction in line with the humerus.

The lower trapezius (LT) was tested as described by Hislop et al (Figure 5). The participant was positioned prone on a plinth with the shoulder abducted to 140° and the humerus laterally rotated where the thumb pointed toward the ceiling. Again, the location of the dynamometer was modified and positioned on the spine of the scapula approximately 2/3 of the distance from the root of the spine to the posterolateral angle of the acromion. Collecting strength measures of the lower trapezius by placing the dynamometer on the spine of the scapula has been determined to be a valid method of assessment. The resistance was applied in a superior and anterolateral direction in line with the humerus.

The supraspinatus (SS) was evaluated as described by Celik et al (Figure 6). The participant was seated with the dominant arm positioned in 90° of shoulder scaption (30° anterior to the frontal plane) with the thumb pointed toward the ceiling. The dynamometer was positioned on the upper arm just proximal to the elbow, and the resistance was applied in a downward direction.
The medial (MR) and lateral (LR) rotators were tested as described by Riemann et al.26 (Figures 7 and 8). The participant was seated with a bolster placed between the dominant upper arm and thorax to maintain a position of 30° abduction and 30° flexion of the shoulder. The elbow was positioned at 90° of flexion, while the forearm was positioned in 0° pronation/supination and aligned parallel to the sagittal plane to achieve approximately 30° of lateral rotation of the shoulder. The dynamometer was placed over the distal radioulnar joint on the volar and dorsal surfaces for the medial and lateral rotators, respectively.

The same investigator performed all the manual muscle tests in this study. For each test, the peak force (N) from three trials was averaged, normalized to body weight (N), and used for data analysis. Excellent within-session, intrarater reliability (ICC3,1 = .920 – .970) was demonstrated for all manual muscle tests over the duration of data collection. In addition to the normalized strength data, strength ratios (UT/LT, UT/MT, LT/MT, SA/UT, SA/MT, SA/LT, and LR/MR) were calculated by dividing the averaged peak force of one muscle by the other.

Statistical Analyses
Descriptive statistics were calculated for demographic data. A two-way mixed analysis of variance was used to determine differences in strength between those with and without scapular dyskinesis, with manual muscle tests (UT1, UT2, SA, MT, LT, SS, MR, and LR) being the repeated factor. If a significant main effect for manual muscle tests was detected, pairwise comparisons were made using a Bonferroni adjustment. Also, a two-way mixed analysis of variance was used to determine differences in strength ratios between those with and without scapular dyskinesis, with strength ratios (UT/LT, UT/MT, LT/MT, SA/UT, SA/MT, SA/LT, and LR/MR) being the repeated factor. If a significant interaction was detected, pairwise comparisons were made between groups for each repeated factor, and a Bonferroni adjustment was made for multiple comparisons. All statistical analyses were calculated using SPSS version 22 (IBM Corporation, Armonk, NY), and the level of significance was set a priori at \( \alpha = .05 \).

RESULTS
Demographic data for the 13 matched-pairs are presented in Table 1. For strength comparisons (Table 2), no significant interaction effects (\( F_{1,825,43.794} = 1.03, p = .343 \)) were observed between manual muscle tests and scapular dyskinesis. Also, no significant main effects were demonstrated for scapular dyskinesis (\( F_{1,24} = .380, p = .543 \)); however, significant main effects for manual muscle tests were revealed (\( F_{1,825,43.794} = 239.582, p < .001 \)). For the strength ratios analysis (Table 3), no significant interaction effects (\( F_{1,834,44.015} = 1.933, p = .160 \)) or main effects for scapular dyskinesis (\( F_{1,24} = 2.517, p = .126 \)) were observed. Although significant main effects for strength ratios were revealed, these effects were not a focus of this study.
plausible that strength deficits would be observed in healthy individuals with scapular dyskinesis. However, the results of the current study challenge the idea that healthy individuals with scapular dyskinesis have strength deficits. The results of this study are further supported in that strengthening programs designed to improve shoulder complex strength do not appear to resolve scapular dyskinesis. Therefore, it may be suggested that gross strength is not a contributory factor in the development of scapular dyskinesis. While the intent of this study was to determine if any strength differences existed, it was interesting to find such a disproportionate number of those with scapular dyskinesis. The disproportionate number of those with scapular dyskinesis along with no differences in strength in a sample of healthy college-aged individuals calls into question the clinical relevance of scapular dyskinesis as a movement impairment. These data may suggest that scapular dyskinesis in healthy individuals is no more than a normal variation of scapular motion. Furthermore, these data may explain the common occurrence and inconsistent patterns of scapular dyskinesis that occur in symptomatic individuals. Nonetheless, these data should not detract from evaluating and considering the role that scapular dyskinesis plays.

DISCUSSION

It was hypothesized that strength differences would exist between healthy individuals with and without scapular dyskinesis, which may serve as a causative factor for scapular dyskinesis. However, the results of this study demonstrated no significant differences in strength or strength ratios of the scapular stabilizers and rotator cuff when compared between those healthy shoulders with and without scapular dyskinesis. To the authors’ knowledge, this was the first study to compare strength measures collected from a sample of healthy participants with and without scapular dyskinesis.

Scapular dyskinesis is commonly associated with numerous pathologies of the shoulder; however, it is not well understood if scapular dyskinesis is the cause or result of the injury. Muscle performance, specifically muscular weakness, has been implicated as a causal factor of scapular dyskinesis based on studies involving symptomatic patients. Rehabilitation programs focused on restoring muscle imbalances of the scapular stabilizers have been demonstrated to restore strength of the rotator cuff in symptomatic overhead athletes. Therefore, if muscular performance is in fact a contributory factor then it is plausible that strength deficits would be observed in healthy individuals with scapular dyskinesis. However, the results of the current study challenge the idea that healthy individuals with scapular dyskinesis have strength deficits. The results of this study are further supported in that strengthening programs designed to improve shoulder complex strength do not appear to resolve scapular dyskinesis. Therefore, it may be suggested that gross strength is not a contributory factor in the development of scapular dyskinesis. While the intent of this study was to determine if any strength differences existed, it was interesting to find such a disproportionate number of those with scapular dyskinesis. The disproportionate number of those with scapular dyskinesis along with no differences in strength in a sample of healthy college-aged individuals calls into question the clinical relevance of scapular dyskinesis as a movement impairment. These data may suggest that scapular dyskinesis in healthy individuals is no more than a normal variation of scapular motion. Furthermore, these data may explain the common occurrence and inconsistent patterns of scapular dyskinesis that occur in symptomatic individuals. Nonetheless, these data should not detract from evaluating and considering the role that scapular dyskinesis plays.

| Table 1. Participant Demographics for Matched-Pairs Analysis |
| --- | --- | --- | --- |
| Variable | With Dyskinesis | Without Dyskinesis | p |
| Age (y ± SD) | 21.5 ± 1.2 | 22.5 ± 2.6 | .188 |
| Height (cm ± SD) | 170.1 ± 9.0 | 167.5 ± 7.1 | .420 |
| Mass (kg ± SD) | 72.7 ± 14.6 | 69.3 ± 11.9 | .523 |
| BMI (kg/m² ± SD) | 24.9 ± 3.4 | 24.6 ± 2.8 | .770 |
| Sex (n) | 3 males; 10 females | 3 males; 10 females | |
| Arm Dominance (n) | 0 left; 13 right | 2 left; 11 right | |
| BMI = body mass index. |

| Table 2. Manual Muscle Test Data for Matched-Pairs Analysis |
| --- | --- | --- | --- |
| Muscle | With Dyskinesis | Without Dyskinesis | Total |
| Upper Trapezius 1 | 0.292 ± 0.046 | 0.328 ± 0.085 | 0.310 ± 0.069 |
| Upper Trapezius 2 | 0.271 ± 0.047 | 0.277 ± 0.099 | 0.274 ± 0.076 |
| Serratus Anterior | 0.145 ± 0.029 | 0.149 ± 0.036 | 0.147 ± 0.034 |
| Middle Trapezius | 0.137 ± 0.013 | 0.135 ± 0.022 | 0.136 ± 0.018 |
| Lower Trapezius | 0.105 ± 0.013 | 0.109 ± 0.028 | 0.107 ± 0.023 |
| Supraspinatus | 0.097 ± 0.015 | 0.105 ± 0.028 | 0.101 ± 0.022 |
| Medial Rotators | 0.089 ± 0.017 | 0.091 ± 0.028 | 0.090 ± 0.023 |
| Lateral Rotators | 0.060 ± 0.012 | 0.060 ± 0.014 | 0.060 ± 0.013 |

Data are presented as normalized strength values (M ± SD) calculated by averaging the maximum force (N) of three trials then dividing by body weight (N) for each muscle, respectively. Significantly greater than those listed below it. Significantly greater than lower trapezius, supraspinatus, medial and lateral rotators. Significantly greater than medial and lateral rotators. Significantly greater than lateral rotators.
in symptomatic patients. Furthermore, there is sufficient evidence to support the use of a rehabilitation program focused on restoring scapular stabilizer recruitment and neuromuscular control.7

The prevalence of scapular dyskinesis is unknown in the healthy population, but it appears to be quite common, if not more common, than what is presently considered to be “normal” scapular motion. In the present study, 68% (27/40) of the overall sample presented with aberrant scapular motion, which led to the utilization of a matched-pairs analysis. According to the literature, scapular dyskinesis has been shown to be present in 50 – 61% of healthy overhead athletes.9,10,14,42 McClure et al27 used overhead athletes that were moderately healthy (included individuals with pain rated up to seven using a 10-point pain scale) to establish reliability of the scapular dyskinesis test, and reported 85% of participants displayed obvious scapular dyskinesis. While their study did not account for arm dominance, it adds to the argument that aberrant scapular motion is present more often than not in healthy populations. Thus, further investigations are warranted to determine the prevalence of scapular dyskinesis in the healthy population.

Significant differences were observed in strength between several of the muscles tested when the two scapular dyskinesis groups were combined (Table 2). Due to a lack of significant differences between the muscles tested, a specific rank order could not be produced. However, several trends were identified that resulted in the following generalized order: the UT generated the greatest amount of force, followed by the SA and MT, LT, SS, MR, and the LR generated the least amount of force. Interestingly, this generalized order is nearly identical to normative data collected via handheld dynamometry using similar testing procedures.26,27 In addition to strength data, strength ratios (Table 3) were calculated that have been reported in normative studies,26,27 or have been the focus of rehabilitation programs aimed at restoring balance of the scapular stabilizers.7,22,23 No significant differences were revealed for any of the strength ratios between the scapular dyskinesis groups (Table 3). The scapular stabilizer ratios calculated from the present study correspond well to those reported by Turner et al.27 However, the LR/MR ratios (0.675 – 0.676) appear to be smaller than those reported by Riemann et al,26 which ranged from 0.86 – 0.92.

It has commonly been suggested that decreased muscle performance of the shoulder musculature is present in individuals with scapular dyskinesis.6-8 However, the authors of these papers primarily reference studies that did not control for scapular dyskinesis, but were based on electromyographic data that demonstrated altered activation patterns of the scapular stabilizers in symptomatic shoulders (e.g., impingement).5-8 Few studies have demonstrated strength deficits of the shoulder musculature in individuals with scapular dyskinesis.10,22,23 Merolla and colleagues reported infraspinatus (IS)22,23 and SS22 strength deficits in symptomatic overhead athletes with scapular dyskinesis. In both studies, participants completed similar six-month rehabilitation programs designed to improve balance and control of the scapular stabilizers. Significant improvements (p < .01) in IS and SS strength were reported at 3 (IS = 42%,22 36%,23 SS = 23%22) and 6 (IS = 43%,22 43%,23 SS = 24%22) months. Based on these results, Merolla and colleagues22,23 speculated that imbalances in the

<table>
<thead>
<tr>
<th>Strength Ratio</th>
<th>With Dyskinesis</th>
<th>Without Dyskinesis</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT/LT</td>
<td>2.791 ± 0.386</td>
<td>3.092 ± 0.668</td>
<td>2.941 ± 0.556</td>
</tr>
<tr>
<td>UT/MT</td>
<td>2.145 ± 0.333</td>
<td>2.423 ± 0.394</td>
<td>2.284 ± 0.384</td>
</tr>
<tr>
<td>LT/MT</td>
<td>0.771 ± 0.080</td>
<td>0.800 ± 0.117</td>
<td>0.785 ± 0.099</td>
</tr>
<tr>
<td>SA/UT</td>
<td>0.503 ± 0.105</td>
<td>0.461 ± 0.055</td>
<td>0.482 ± 0.085</td>
</tr>
<tr>
<td>SA/MT</td>
<td>1.059 ± 0.162</td>
<td>1.106 ± 0.158</td>
<td>1.082 ± 0.159</td>
</tr>
<tr>
<td>SA/LT</td>
<td>1.383 ± 0.229</td>
<td>1.403 ± 0.237</td>
<td>1.393 ± 0.228</td>
</tr>
<tr>
<td>LR/MR</td>
<td>0.676 ± 0.097</td>
<td>0.675 ± 0.118</td>
<td>0.675 ± 0.106</td>
</tr>
</tbody>
</table>

Strength Ratios (M ± SD) were calculated by dividing the averaged peak force of one muscle by the other, respectively. UT = upper trapezius, MT = middle trapezius, LT = lower trapezius, SA = serratus anterior, LR = lateral rotators, and MR = medial rotators.

No significant differences were revealed between groups for any of the strength ratios.
scapular musculature led to an acquired scapular dyskinesis, which compromised the length-tension relationship of the rotator cuff muscles that resulted in weakness of the IS and SS, secondarily. However, the results of these studies should be interpreted cautiously as muscle performance measures were not collected for the scapular stabilizers. Additionally, while all participants were cleared for labroligamentous injuries, chondral lesions, and rotator cuff tears via magnetic resonance imaging, they were all symptomatic at baseline. Therefore, it is purely speculative that scapular dyskinesis was acquired, especially with the growing evidence that scapular dyskinesis is commonly found in healthy overhead athletes.9–11

Others have speculated the same regarding muscle imbalances of the scapular stabilizers, which has led to the development of a scapular repositioning maneuver to test for weakness of the IS and SS.30,31 During this maneuver, the clinician retracts the scapula and provides external stabilization that results in the ability of the rotator cuff in symptomatic individuals with scapular dyskinesis to produce greater strength output when compared to traditional manual muscle testing procedures. Yet, strength improvements have been observed in healthy, asymptomatic individuals when utilizing the repositioning maneuver as well.31,32 In contrast, Smith and colleagues43 demonstrated significantly lower measures of shoulder elevation strength when the scapula was positioned in retracted and protracted positions as compared to the normal resting position in a sample of healthy individuals without scapular dyskinesis. Nonetheless, these studies indicate scapular positioning has an impact on shoulder strength. The scapular repositioning maneuver was not utilized in the current study, and no significant differences were revealed between the scapular dyskinesis groups. These findings suggest that healthy individuals may position their scapula optimally for strength output regardless of the presence of scapular dyskinesis. Therefore, the clinical usefulness of the repositioning maneuver is debatable and should be interpreted with caution.

In addition to the current study, only one other study has compared strength measures of the MT and LT in asymptomatic individuals with and without scapular dyskinesis. Seitz et al10 reported weakness of the LT by 4% (p = .031) body mass in those with scapular dyskinesis in a sample of asymptomatic overhead athletes. Interestingly, the group with scapular dyskinesis in the current study demonstrated weakness by 4% body mass, but was not found to be significant. The conflicting results may be explained by differences in populations studied as stronger scapular muscles of the dominant shoulder,28,44 and asymmetrical positioning of the scapula are known to occur in healthy overhead athletes.45,46 Additionally, testing methods differed for the manual muscle test as Seitz et al10 applied resistance just proximal to the wrist, whereas the resistance was applied directly to the scapula in the current study. It was thought that a better representation of the strength capabilities of the scapular stabilizers would be achieved by positioning the dynamometer directly over the scapula, which is supported by others.24 In fact, Michener et al24 demonstrated that assessing strength of the lower trapezius with a handheld dynamometer placed over the scapula yielded valid measures when compared against electromyography. However, no data exist that compares strength measures of the scapular stabilizers collected with the dynamometer placed in the two different positions. Nonetheless, by positioning the dynamometer at the wrist, additional factors (e.g., glenohumeral strength) contribute to force generation that may disguise the true strength capabilities of the targeted musculature.

When evaluating the results of the current study, several limitations were identified that warrant acknowledgment. First, the generalizability of the results are limited to healthy, college-aged individuals, which consisted mostly of females (77%) and may or may not have included overhead athletes. Additionally, only data from the dominant arm was used in this study. Inclusion of data from the non-dominant arm in future studies would aid in the generalizability of the results and in determining the prevalence of scapular dyskinesis. A second limitation is the large amount of variability that is inherent to scapular kinematics, yet a dichotomous method was utilized to categorize those with and without scapular dyskinesis. Other investigators have subcategorized movements of the scapula as normal, subtle, or obvious to maximize the detection of differences.47,48 However, for the purposes of this study, the subtle and obvious categories were combined.
and the yes/no method was utilized as it was speculated that clinicians are more likely to treat symptomatic patients the same regardless of the “degree” of scapular dyskinesis. Studies have indicated better measures of agreement in identifying scapular dyskinesis utilizing a dichotomous method over other sub-categorization methods as defined by Tate et al and Kibler et al. Regardless of the fact that the presence of scapular dyskinesis was based upon an established criteria and the implementation of that criteria by a single observer, a large amount of variability was noted in the scapular motion in the scapular dyskinesis group. Through the implementation of the match pair’s criteria and merely by chance alone, those with a lesser degree of scapular dyskinesis were not included in the matched-pairs. This adds merit to the current findings because excluding those participants should have maximized any potential differences between the groups. Lastly, a ceiling effect was observed with the UT1 method as a few of the male participants were able to lift the investigator from the floor, which negated the ability to collect a maximum effort by these individuals. This, along with a similar experience by Turner et al, prompted the use of the UT2 method. While significant differences were revealed between the two methods, the overall results in the matched-pairs analysis were not likely affected as neither measure revealed significant differences between the two scapular dyskinesis groups.

**CONCLUSION**

The results of this study indicate that no differences in shoulder strength exist between individuals with and without scapular dyskinesis in a healthy population of college-aged individuals with no history of neck and shoulder pathology. As such, gross strength is not likely to be a contributing factor to the development of scapular dyskinesis, whereas other muscle performance factors, such as neuromuscular control, may be. Moreover, this study adds to a growing body of evidence that scapular dyskinesis is commonly found in healthy individuals.

**REFERENCES**

13. Clarsen B, Bahr R, Andersson SH, et al. Reduced glenohumeral rotation, external rotation weakness and scapular dyskinesis are risk factors for shoulder injuries among elite male handball players: a


ABSTRACT

**Background:** Weakness of the rotator cuff muscles can lead to imbalances in the strength of shoulder external and internal rotators, change the biomechanics of the glenohumeral joint and predispose an athlete to injury. Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that has demonstrated promising results in a variety of health conditions. However few studies addressed its potential approach in the realm of athletics.

**Hypothesis/Purpose:** The purpose of this study was to investigate if transcranial direct current stimulation (tDCS) technique increases the isometric muscle strength of shoulder external and internal rotators in handball athletes.

**Study Design:** Randomized, double-blind, placebo-controlled, crossover study.

**Methods:** Eight female handball players aged between 17 and 21 years (Mean = 19.65; SD = 2.55) with 7.1 ± 4.8 years of experience in training, participating in regional and national competitions were recruited. Maximal voluntary isometric contraction (MVIC) of shoulder external and internal rotator muscles was evaluated during and after 30 and 60 minutes post one session of anodal and sham current (2mA; 0.057mA/cm²) with a one-week interval between stimulations.

**Results:** Compared to baseline, MVIC of shoulder external and internal rotators significantly increased after real but not sham tDCS. Between-group differences were observed for external and internal rotator muscles. Maximal voluntary isometric contraction of external rotation increased significantly during tDCS, and 30 and 60 minutes post-tDCS for real tDCS compared to that for sham tDCS. For internal rotation MVIC increased significantly during and 60 minutes post-tDCS.

**Conclusions:** The results indicate that transcranial direct current stimulation temporarily increases maximal isometric contractions of the internal and external rotators of the shoulder in handball players.

**Level of Evidence:** 2

**Key words:** Isometric contraction, handball, shoulder rotator muscles, Transcranial direct current stimulation (tDCS)

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**Funding**

No funding was provided for this study.

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**INTRODUCTION**

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique for modulation of brain activity and excitability that has demonstrated promising results in a variety of health conditions, such as chronic pain, depression and chronic stroke. For healthy athletes, tDCS is potentially useful due to the possibility of ergogenic or facilitatory effect in muscle performance and sports’ skills. Previous authors have shown that an application of anodal tDCS (a-tDCS) over primary motor cortex (M1) of healthy individuals improves muscle endurance; enhances pinch force in the lower leg (grip force of the great toe and the second toe) and enhances the consolidation of ballistic thumb movement. Other researchers investigated the effect of tDCS over the left prefrontal cortex and found an improvement in performance of a dexterity-demanding task.

Specifically for muscle performance tasks, the effect of tDCS seems to be related to alterations in motor unit recruitment strategies. Taken together these results suggest that tDCS could be useful as an auxiliary tool for physical and motor performance training. However despite some evidence of the benefits of tDCS in healthy volunteers, few studies have addressed its potential approach in the realm of athletics.

Increase in muscle capabilities even at minimum levels can be useful for athletes, especially for sports demanding excessive and repetitive efforts. For instance, in throwing athletes such as handball players, muscle weakness of external shoulder rotators is associated with shoulder injury. Muscle imbalance between the external and internal rotator muscles is also observed in handball players. Thus optimal muscle function is highly desired to avoid shoulder injury and impairment in sports performance. The possibility of identifying a safe ergogenic aid to optimize muscle recruitment and muscle strength is of extreme interest to athletes, coaches and researchers, and modulation of the motor cortex by tDCS may be an easy and helpful strategy in this condition. The purpose of this study was to investigate whether tDCS technique increases the isometric muscle strength of shoulder external and internal rotators in handball athletes. Maximal voluntary isometric contraction (MVIC) was evaluated during and after the application of anodal and sham current to test the modulatory and plastic effects of tDCS on isometric muscle strength, respectively.

**METHODS**

**Subjects**

This randomized, double-blind, placebo-controlled crossover study included eight female handball athletes participating in regional and national competitions (Table 1). All participants were in the pre-season training period and were instructed not to perform any kind of strenuous exercise and not to ingest alcoholic or caffeinated drinks during the two weeks of data collection. Athletes with suspected or confirmed pregnancy, complaints of pain in the upper limbs with intensity ≥ 3, evaluated by numerical pain rating scale (NPRS 0-10), medical history or personal report of epilepsy or convulsive event, or the use of drugs with central action were excluded. The study was approved by the local Research Ethics Committee under the protocol number 269.011 and the participants signed the informed consent.

**Experimental paradigm**

The study was conducted in two weeks. In the first week, the participants were randomly distributed based on an online generating random numbers software (www.randomization.com) into two groups: (1) real anodal tDCS or (2) sham anodal tDCS. The randomization and allocation concealment were carried out by an external collaborator, not involved in the study, through individual opaque envelopes containing the identification number of the participants and their type of stimulation (real / sham). In the second week the type of stimulus was inverted between the participants. Muscle performance evaluation was carried out (1) immediately pre-tDCS, (2) during tDCS (after 13 min); (3) 30 minutes post-tDCS, and (4) 60 minutes post-tDCS. Evaluations during and after the application of anodal current

<table>
<thead>
<tr>
<th>Table 1. Participant’s characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Body Mass (Kg)</td>
</tr>
<tr>
<td>Height (m)</td>
</tr>
<tr>
<td>Handball experience (years)</td>
</tr>
<tr>
<td>Week training (hours)</td>
</tr>
</tbody>
</table>
were designed to test the modulatory and plastic effects of tDCS, respectively. The same researcher performed all the evaluations. He did not know the characteristics of the applied stimulations (real or simulated), nor did the participants.

**Muscle Strength Evaluation**

Initially, the participants were instructed to perform warm-up exercise for five minutes on an upper body ergometer. Afterwards, they made two attempts of submaximal isometric voluntary contraction of the external and internal rotator muscles, in the dominant limb, to familiarize themselves with the methods of muscle strength evaluation. One minute of rest was allowed between contractions. The maximum voluntary isometric contractions of the internal and external rotator muscles in the dominant limb were collected. To minimize the risks of muscle fatigue during MVIC tests, all participants were allowed a rest interval of one minute between contractions. Counter-balancing of the rotator muscles was performed to minimize the participant's learning factor. To perform the tests, the hand held dynamometer (MicroFet2, Hoggan Health Industries, USA) was positioned at the athlete’s wrist area (2 cm below the radial styloid process) on the dorsal aspect of the wrist to test the lateral rotators, and ventral aspect to test the internal rotators.

A rigid band was used to stabilize the dynamometer. The participants remained in the supine position, with shoulder at 90° of abduction and the elbow was flexed to 90°. During the test the assessor stabilized the participant’s shoulder to avoid accessory movements (Figure 1).

**Anodal tDCS**

Anodal tDCS was applied through a battery powered DC generator (Activadose II, USA) using two electrodes measuring 5 x 7 cm (35 cm²) (Ibramed, Brazil) covered with an electrode sponge, saturated with physiological saline solution, and fixed onto the head by means of velcro straps. The electrodes were mounted in accordance with the International 10-20 EEG System for optimal focalization of the primary motor cortex.

The electrode with the positive charge (anode – excitatory pole) was positioned at C3 or C4 (contra-lateral to the dominant limb), and the electrode with the negative charge (cathode – inhibitory pole) in the ipsilateral supraorbital region of the dominant limb (Figure 1). Real tDCS was applied with electric current amplitude of 2 mA, electric current density of 0.057 mA/cm², for 20 minutes. Sham tDCS was applied with the same parameters, maintaining the electrodes in place for 20 minutes over the head, but stimulation was on for only the first 30 seconds.

During the application of tDCS the participants remained seated. After 13 minutes of stimulation, they lay down on the stretcher for the MVIC evaluation, corresponding to time interval 2 (during tDCS). The decision was made to wait until 13 minutes of stimulation had passed, because previous studies have demonstrated that this was the minimum time required to obtain an increase in cortical excitability for up to 1.5 hours. The adverse effects were evaluated after each application through spontaneous reports of any unpleasant sensations such as burning, tingling, itching, headache, or nausea.

**Statistical Analysis**

The averages of three maximum contractions in each time interval were analyzed separately with regards to the external and internal rotator muscles. Normalization of the data was performed by using
DISCUSSION
The aim of this study was to investigate whether anodal tDCS applied to the motor cortex has ergogenic effects on isometric strength of shoulder muscles in handball players. The results showed that anodal tDCS can induce a temporary and progressive increase in MVIC of shoulder rotator muscles, which did not happen in sham tDCS intervention.

Compared to baseline muscle strength, real tDCS improved 10.2, 18.6 and 19.3% for external rotation during and after 30 and 60 minutes post-stimulation, respectively. Internal rotation muscles showed improvement of 5.6%, 11.1% and 15.1%, respectively. For sham tDCS no improvements were observed for external and internal rotation in all time frames analyzed. When compared to sham tDCS, stimulation results also showed increases in MVIC during and after tDCS for external and internal rotator muscles. These results indicate that tDCS can temporarily induce an incremental increase in maximal isometric strength of shoulder rotators in previously physically conditioned subjects.

There is some evidence in the literature that tDCS influences fatigue and muscle strength in normal

### Table 2. Mean (SD) for external and internal muscle strength (N/Kg) across intervals and mean difference (95% CI) within and between groups

<table>
<thead>
<tr>
<th>External Rotation</th>
<th>tDCS intervals</th>
<th>Within-group differences</th>
<th>Between-group differencesa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T0  T20 T50 T80</td>
<td>T20-T0 T50-T0 T80-T0</td>
<td>T20         T50         T80</td>
</tr>
<tr>
<td>Real tDCS</td>
<td>0.9 (0.1) 1.0 (0.1) 1.1 (0.2) 1.1 (0.1)</td>
<td>0.1* (0.0 to 0.2) 0.2* (0.1 to 0.3) 0.2* (0.1 to 0.3)</td>
<td>0.1* (0.0 to 0.2) 0.2* (0.1 to 0.3) 0.2* (0.1 to 0.3)</td>
</tr>
<tr>
<td>Sham tDCS</td>
<td>0.9 (0.2) 0.9 (0.1) 0.9 (0.2) 0.9 (0.1)</td>
<td>(-0.1 to 0.1) (-0.1 to 0.1) (-0.2 to 0.1)</td>
<td></td>
</tr>
<tr>
<td>Internal Rotation</td>
<td>Real tDCS</td>
<td>0.9 (0.1) 1.0 (0.1) 1.1 (0.1) 1.1 (0.1)</td>
<td>0.1 (0.0 to 0.2) 0.1* (0.0 to 0.2) 0.1* (0.0 to 0.2)</td>
</tr>
<tr>
<td></td>
<td>Sham tDCS</td>
<td>0.9 (0.1) 0.9 (0.1) 0.9 (0.2)</td>
<td>0.0 (0.0 to 0.0) (-0.1 to 0.1) (-0.1 to 0.1)</td>
</tr>
</tbody>
</table>

aBetween-group differences are adjusted. *Significant difference (p<0.05).

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volunteers. Cogiamanian et al. found increased isometric force endurance in a submaximal isometric contraction of elbow flexors after 10 minutes of anodal but not cathodal tDCS applied over the motor areas of the cerebral cortex (1.5mA, 0.043mA/cm²).⁶ In a similar protocol of submaximal contraction of elbow flexors, Williams et al. demonstrated that anodal, but not sham tDCS (1.5mA, 0.043mA/cm²) enhanced time to task failure during but not at the end of task execution. For lower limbs, Tanaka and collaborators demonstrated that 10 minutes of real but not sham or cathodal tDCS applied to the motor cortex (2mA, 0.057mA/cm²) could temporarily enhance maximal leg pinch.

A reasonable explanation for these improvements in muscle strength is that the enhancement of corticospinal excitability via tDCS may alter motor unit recruitment strategies.⁷,¹¹,¹² Hence, as more motor units are recruited, more muscle strength is generated. Although the authors did not measure muscle activation, the current results are likely to be more related to optimization of neuromuscular function than other effects (such as motivational effects), as the same participants were assessed in both conditions in the crossover design.

In the current study, changes in MVIC during real stimulation indicated that tDCS technique could positively modulate the isometric strength of external and internal shoulder rotators in handball players. Muscle imbalance, as represented by the ratio of external to internal rotators, is often present in handball players¹⁴ and may lead to injury.²² tDCS could be applied as a complementary tool in muscle strengthening programs to help counteract these imbalances in combination with specific exercises, as this transitory increment in muscle strength per se does not necessarily result in improved sports skills if considered as an unique intervention.⁵

In this context, tDCS could act to increase sports performance through facilitating the activation of corticospinal tract and potentiating the entire motor pathway. Favorable results have been demonstrated when tDCS is associated with active exercises. Anodal tDCS (2mA, 0.08mA/cm²) combined simultaneously with voluntary exercise produces a two-fold increase in the amplitude of motor excitability compared with tDCS or exercise alone.²³ Nonetheless, the effect of tDCS combined with exercise seems to be dependent on the characteristic of exercises, such as type of muscle contractions.²⁴ It is possible that tDCS has a relevant effect in specific physical fitness and in specific conditions. The “ideal” protocols for motor cortex modulation that fit the needs of athletes and coaches still need further investigation.

The present study has some limitations and factors that may have influenced the results. (1) Small sample size: Given the high variability between subjects during and after tDCS application these results must be replicated with large samples; (2) Variability in muscle representation in the primary motor cortex: transcranial magnetic stimulation was not utilized to determine the hot spot for external and internal muscle rotators in the cortex, which would have helped to potentiate the effects of the intervention; (3) The authors did not include cathodal stimulation. Although many studies have demonstrated that cortical excitability is polarity-dependent,²⁰,²⁵ other studies have verified that anodal polarity may exert an inhibitory effect during motor tasks²⁶ just as cathodal polarity may exert an excitatory effect according to the intensity of stimulation.²⁷ Future studies should include cathodal stimulation to investigate if the effects of tDCS on muscle strength are dependent on the polarity.

CONCLUSION
The results of this randomized, crossover trial indicate that transcranial direct current stimulation temporarily increases the isometric strength of the shoulder rotator muscles in handball players.

REFERENCES


ABSTRACT

Background: Military organizations use movement quality screening for prediction of injury risk and performance potential. Currently, evidence of an association between movement quality and performance is limited. Recent work has demonstrated that external loading strengthens the relationship between movement screens and performance outcomes. Such loading may therefore steer us toward robust implementations of movement quality screens while maintaining their appeal as cost effective, field-expedient tools.

Purpose: The purpose of the current study was to quantify the effect of external load-bearing on the relationship between clinically rated movement quality and tactical performance outcomes while addressing the noted limitations.

Study Design: Crossover Trial.

Methods: Fifty young adults (25 male, 25 female, 22.98 ± 3.09 years, 171.95 ± 11.46 cm, 71.77 ± 14.03 kg) completed the Functional Movement Screen™ with (FMS™W) and without (FMS™C) a weight vest in randomized order. Following FMS™ testing, criterion measures of tactical performance were administered, including agility T-Tests, sprints, a 400-meter run, the Mobility for Battle (MOB) course, and a simulated casualty rescue. For each performance outcome, regression models were selected via group lasso with smoothed FMS™ item scores as candidate predictor variables.

Results: For all outcomes, proportion of variance accounted for was greater in FMS™W (R² = 0.22 [T-Test], 0.29 [Sprint], 0.17 [400 meter], 0.29 [MOB], and 0.11 [casualty rescue]) than in FMS™C (R² = 0.00 [T-Test], 0.11 [Sprint], 0.00 [400 meter], 0.19 [MOB], and 0.00 [casualty rescue]). From the FMS™W condition, beneficial performance effects (p<0.05) were observed for Deep Squat (sprint, casualty rescue), Hurdle Step (T-Agility, 400 meter run), Inline Lunge (sprint, MOB), and Trunk Stability Push Up (all models). Similar effects for FMS™C item scores were limited to Trunk Stability Push Up (p<0.05, all models).

Conclusions: The present study extends evidence supporting the validity of load-enhanced movement quality screening as a predictor of tactical performance ability. Future designs should seek to identify mechanisms explaining this effect.

Level of Evidence: 3

Key Words: Movement quality, tactical athlete, talent identification, screening
INTRODUCTION
Recent recruiting cycles have been remarkably successful for the U.S. military. Accession goals with respect to quantity and quality were exceeded, in many cases by substantial measure. Such a favorable recruiting environment largely eliminated the need for consideration of pre-accession performance screening systems. However, the same reports that extol the recruiting successes of recent years also express concern about potential future challenges. Owing to a combination of defense budget cuts and economic alternatives for the recruitment population, it will likely be more difficult for the military to meet its accession goals over the next decade. This prospect of future austerity has accordingly renewed focus on the discussion of minimizing preventable attrition due to substandard fitness or injury. Because multi-faceted performance batteries can be cumbersome, consideration is warranted for efficient clinical tools that can identify at-risk military candidates in pre-accession settings.

One solution that may hold promise as a cost effective and field-expedient option for preventing performance-related personnel loss is movement quality screening. The use of such screens has increased substantially in recent years. In addition to classifying individuals by injury risk, movement screens have also been applied as a method of predicting performance in tactical athletes and other populations. In this endeavor, most research has failed to show a relationship between clinically rated movement scores and performance outcomes—a lack of association which likely stems from two sources. First, relatively undemanding movement tests may not present a challenge sufficient to highlight deficiencies relevant to athletic performance. Accordingly, it has been suggested that adjusting screening practices to increase specificity or difficulty may increase the likelihood of detecting deficiencies clinically.

The second limitation of movement screening as a correlate of physical performance relates to current methods for scoring and analyzing data. Item scores are most commonly rated on an ordinal scale and summed into a total. While a composite representation of test performance has its appeal, this practice is appropriate only if the construct underlying the total score is unidimensional. In the case of clinical movement screens, a growing body of evidence would suggest this is not the case. More detailed information can be found in the item scores themselves, although certain considerations must be addressed concerning their analysis. In addition to a rank order structure which is difficult to accommodate in linear or logistic regression, direct analysis of component score data in existing clinical movement screens would substantially increase the dimensionality of a prediction model.

A recent investigation in young, recreationally active non-service members demonstrated that Functional Movement Screen™ (FMS™) tests under load show increased predictive validity with respect to criterion performance measures specific to the tactical athlete. In the same context, that study also demonstrated the utility of regularization techniques designed to accommodate high-dimensional regression problems with ordered predictors. The intention in combining these two modifications in approach was to help bring the sports medicine community closer to a field-expedient, feasible means of conducting pre-accession screening for performance deficits.

While the above-mentioned study showed promising results, certain factors limit the generalizability of their findings. First, it was conducted using a relatively small sample size. Second, this sample did not contain an even balance of men and women. The purpose of the current study was to quantify the effect of external load-bearing on the relationship between clinically rated movement quality and tactical performance outcomes while addressing the noted limitations.

METHODS
Data were collected in a laboratory setting by a single investigator experienced in the required measurement techniques. Participation was limited to individuals between 18-34 years of age in order to reflect the recruitment pool for military and tactical occupations. Subjects were additionally required to be free from recent (< six months) injury and to accumulate a minimum of 90 minutes/week of physical activity. All subjects provided written consent to participate and completed a physical activity readiness questionnaire (PAR-Q) before data collection.
Procedures
This study was approved by the Institutional Review Board at The University of North Carolina at Greensboro. A total of fifty recreationally active adults participated in the study (25 female: 22.00 ± 2.02 years, 165.40 ± 10.24 cm, 63.98 ± 11.07 kg; 25 male: 23.96 ± 3.74 years 178.82 ± 7.51 cm, 79.66 ± 12.66 kg). Subjects reported to the laboratory for a single data collection session. Following consent and completion of the PAR-Q, the Functional Movement Screen™ was administered under two conditions (wearing a weight vest: FMS_w, and not wearing a weight vest: FMS_n) in randomized order. Finally, participants completed a battery of physical performance tests.

Functional Movement Screen™
Following a familiarization round, the FMS™ 19,20 was administered both with and without an 18.10 kg weight vest (MiR Vest Inc., San Jose, CA). This is comparable to loads used in previous investigations on the topic of tactical athleticism,21,22 as well as those used in clinical screens designed to predict physical performance.6 Testing conditions were administered back-to-back in randomized order by an investigator proficient in the use of FMS™ testing. Scores for component tests were assigned based on a 1-3 scale according to the criteria outlined in the FMS™ protocol.19,20

Physical Performance Tests
Following completion of the FMS™ in both testing conditions, participants performed a 10-minute cycle ergometer warm up during which they were instructed to target an RPE of 13 (“Somewhat Hard”). They then began a series of five performance tests comprising assessments from previous tactical performance work.22,23 Instructions were to complete each individual test as quickly as possible. Physical performance tests were administered in the following order for all subjects: 1) T-Agility test, 2) 27.43 meter sprints, 3) 400 meter run, 4) Mobility for Battle (MOB), and 5) simulated casualty rescue.

Completion time for both the Agility T-Test and sprints was recorded using an infrared timing gate (Brower Timing Systems, Draper, UT). Subjects began on the starting mark with one foot positioned on a start-on-release trigger. When directed, subjects performed the following sequence: forward sprint 9.14 m (10 yds), right side-shuffle 4.57 m (5 yds), left side-shuffle 9.14 m (10 yds), right side shuffle 4.57 m (5 yds), back peddle 9.14 m (10 yds). The timing gates were applied similarly in the 27.43 m sprints. For both the Agility T-Test and the 27.43 sprint, each effort was followed by approximately 60 seconds of rest regardless of whether performing another trial of the same test or proceeding to the next task.

Because of logistical restrictions, completion time for the remaining tests was recorded using a handheld stopwatch. Courses for the 400 m run and Mobility for Battle23 (MOB) were mapped with cones in an indoor gymnasium. The 400 m run was administered as a series of 4.5 laps around the periphery of the gym space. The MOB, designed as a multifaceted test incorporating several soldier-relevant field maneuvers, was organized in stations according to the methods described in Crowder et al.23 Participants were allotted up to five minutes of recovery time upon finishing each of the 400 m and MOB tests.

The final test was a simulated partner rescue, in which subjects were required to drag a 68.04 kg (150 lbs.) dummy across a distance of 45.72 m (50 yds). The dummy was fashioned from sandbags wrapped in carpet with a handle attached to one end. Completion time was recorded after the final bag crossed the finishing line.

Statistics
Several researchers have noted the limitations of analyzing the FMS™ composite score.14-16 The item scores themselves are likely the better source of information, although extra care must be taken to select appropriate prediction models from a multitude of candidate predictor variables. Further, more of the information contained in the item scores can be preserved by using methods that account for their ordinal structure. Each of these challenges can be addressed via penalization. Application of regression penalization algorithms is common in, for example, genome-wide association studies (GWAS),24 in which the number of predictors often greatly exceeds the number of observations. The effect of penalization is to shrink large coefficients and thereby reduce bias toward data characteristics, which are unique to a given sample. Additional penalization can be applied to smooth the differences between successive levels.
of a predictor. Thus, these techniques offer an attractive solution to the problems that arise when analyzing FMS™ item score data.

In the current analyses, a group lasso penalty was first applied to select an appropriate model. Differences between neighboring levels within the retained predictors were then smoothed using a second penalization algorithm. The same penalty parameter (Λ) was used in each step, identified as the value of Λ, which minimized cross-validation error in the group lasso. The final step after model selection and smoothing was to construct bootstrap 95% confidence intervals of the estimated coefficients using the bias-corrected and accelerated method. Each of these steps was completed using R v3.1.0 with ordPens 0.3-42 and grpreg 2.8-5 packages.

RESULTS
Descriptive statistics regarding physical performance outcomes are presented in Table 1. Model summaries are presented in Table 2 while smoothed and unsmoothed coefficients, along with their respective bootstrap confidence intervals, are presented in Tables 3 (Agility T-Test, Sprint, and 400 meter outcomes) and 4 (MOB and Partner Rescue outcomes). A non-zero R² was observed in only three of the models corresponding to the unweighted condition. The first of these was the Sprint model, in which penalized FMS™ item scores accounted for 11% of the variance in time to completion. The second and third were the penalized and unpenalized MOB models which, respectively, accounted for 19% and 9% of the variance in time to completion. In contrast, non-zero R² values were observed in all models featuring scores from the weighted condition, with variance explained ranging from 11% - 29%.

In the unweighted condition, higher Trunk Stability Push Up scores were predictive of faster completion times for the Sprint and MOB tests. A similar influence was observed for the remaining three performance outcomes, though variation in scores was not

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
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<tbody>
<tr>
<td>T-test</td>
<td>12.81 ± 1.55</td>
</tr>
<tr>
<td>Sprint</td>
<td>3.98 ± 0.54</td>
</tr>
<tr>
<td>400m</td>
<td>93.88 ± 16.60</td>
</tr>
<tr>
<td>MOB</td>
<td>145.74 ± 28.39</td>
</tr>
<tr>
<td>RSQ</td>
<td>23.17 ± 9.48</td>
</tr>
</tbody>
</table>

T-test = T-Agility test
Sprint = 27.43 meter sprint
400m = 400 meter run
MOB = Mobility for Battle assessment
RSQ = simulated casualty rescue

Table 2. Summaries of Penalized and Unpenalized Model Solutions. FMS™C (unweighted) models are shown on the left and FMS™W (weighted) models are shown on the right. Each is presented both with optimized penalization (top) and no penalization (bottom) in adjacent rows. The ‘Features’ column indicates the number of predictors retained at the given level of penalization.

<table>
<thead>
<tr>
<th></th>
<th>Unweighted</th>
<th></th>
<th></th>
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Agility = T-Agility test, Sprint = 27.43 meter sprint, 400m = 400 meter run, MOB = Mobility for Battle assessment, RSQ = simulated casualty rescue, Λ = regression model penalty parameter, CVE = Cross-validation error
explained at the model level. Higher Trunk Stability Push Up scores from the weighted condition were predictive of faster completion times for all measures. Additionally in the weight vest condition, a Hurdle Step score of 3 was predictive of faster Agility T-Test times while a score of 2 or 3 was predictive of faster 400 meter run times. Higher weighted Inline Lunge scores were also associated with performance, with a score of 3 predicting faster Sprint times and a score of 2 or 3 predicting faster MOB times. Interestingly, a weighted Inline Lunge score of 3 was also predictive of slower time to completion on the partner rescue simulation. A similar inverse relationship was observed between 400 m times and scores of 2 or 3 in the weighted Shoulder Mobility test. Finally, a weighted Deep Squat score of 2 was predictive of faster sprint times while a score of 2 or 3 was predictive of faster partner rescue times.

**DISCUSSION**

This study sought to quantify the effect of external load-bearing on the relationship between cost-efficient movement quality screens and tactical performance outcomes. The current findings support the conclusion that external load-bearing strengthens the relationship between movement quality and tactical athleticism. The vast majority of these results demonstrate that better movement quality on the weighted Trunk Stability Push-up, Hurdle Step, Inline Lunge, and Deep Squat tests is predictive of faster completion of the physical performance tests. Very few predictive relationships exist

<p>| Table 3. Coefficients and bootstrap (BCa method) 95% confidence intervals for retained predictors of time to completion of Agility, sprint, and 400 meter. Level indicates the FMS™ item score, for which the reference condition (‘1’) is not shown. |
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| DS = Deep Squat, HS = Hurdle Step, IL = Inline Lunge, SM = Shoulder Mobility, ASLR = Active Straight LegRaise, TSPU = Trunk Stability Push Up, RS = Rotary Stability
between unweighted movement quality and performance tasks. These observations parallel previously reported increases in the predictive validity of FMS item scores related to testing under a standardized external load.\textsuperscript{14} The combination of the present findings with similar results derived from an unrelated sample establishes strong evidence in support of this effect. Before continuing the discussion of the present findings, it should be noted that the authors consider the correlation between movement quality and performance as a function of the common factors that underlie both outcomes. The factors in question are derived from physical fitness models found in the U.S. Army Physical Fitness School doctrine.\textsuperscript{26} As will be detailed later, this conceptual framework may have implications for how movement quality assessments are applied.

In this protocol, the expected finding was that external loading during movement quality assessments would improve prediction of physical performance. While this improvement in prediction was observed, it is interesting to note that the test items driving that improvement were not necessarily the same as those observed previously. Among the items that overlap, weighted Trunk Stability Push Up predicted better performance in all outcomes, as did the unweighted Trunk Stability Push Up for the Sprint.
Also common to both datasets, weighted Hurdle Step predicted faster 400m run times. The previously published data\textsuperscript{14} contains several unique effects in the weighted condition. These include relationships between the Deep Squat and 400m run, the Deep Squat and MOB, and the Hurdle Step and MOB. Two unique performance-inhibiting effects were also noted. Specifically, a 3 on the Inline Lunge or Shoulder Mobility tests predicted slower times in the Partner Rescue task.

Several unique effects were also observed in the current data set. These included the relationships between weighted Inline Lunge and sprint speed, weighted Inline Lunge and MOB times, and weighted Deep Squat and Partner Rescue times. Each of these positive effects might be explained by qualities like muscular strength and balance, which arguably become more critical to movement execution in the weighted condition. Additional beneficial effects specific to the present analysis were observed in the relationships between unweighted Trunk Stability Push Up and all outcomes other than sprint speed. Again, muscular strength is likely a factor, as this test requires a high degree of upper body strength even in the unweighted condition.

Apparently detrimental effects of movement quality in the current dataset included those between weighted Shoulder Mobility and sprint speed, weighted Shoulder Mobility and 400 m times, and unweighted Inline Lunge and Partner Rescue times. In those effects related to the weighted Shoulder Mobility test, it is possible that certain qualities that enable an individual to achieve a high score are beneficial only to a point. For example, an individual who is able to touch fists behind his/her back despite wearing a weight vest might be hypermobile to an extent that interferes with performance. Alternatively, this degree of mobility might reflect a lack of movement restriction associated with typical muscle development. The negative association between unweighted Inline Lunge scores and Partner Rescue times is more difficult to explain and may require further consideration. One possibility is that this reflects a tradeoff between muscular strength/power and coordination in performing this relatively novel movement. In any case, because the current results are based on a larger sample size that is split evenly between men and women, these findings may be more generalizable than previous work.

In many cases, the hypothesized relationship between clinically rated movement behaviors and physical performance has eluded investigators.\textsuperscript{9-11,13} The difficulty in demonstrating this association may be rooted in the relatively low demand of most screening tools or improper analysis. Steps were taken in the present study to address these concerns. Specifically, we incorporated an external loading condition and modeled the effects of item scores on performance outcomes with well-suited statistical techniques. The current results suggest that the relationship between movement and performance can be observed under the proper conditions. These findings may have considerable implications for pre-accession screening strategies in a time during which the cost of performance failure has the potential to increase substantially. Specifically, an inexpensive and easily administered movement assessment could help prevent attrition and washback by complementing existing accession standards.

A natural follow-up question might seek to explain the mechanisms driving this relationship between movement patterns and performance outcomes. Different interpretations of the present findings could be taken to support vastly different approaches to training. Proponents of movement screening frequently consider movement behaviors themselves to be a kind of stand-alone functional criterion.\textsuperscript{5,27} This understanding has recently inspired efforts to identify intervention protocols capable of improving screening scores.\textsuperscript{20,29} An alternative interpretation proposed here would suggest that the utility of clinical screens in this context is that they allow us to see evidence of performance-relevant attributes using a convenient, field-expedient test. Understanding which attributes mediate the relationship between movement and performance may therefore be the more appropriate focus of training and is the subject of ongoing research in our laboratory.

Two limitations should be noted regarding this study. First, participants were recruited primarily from a civilian undergraduate population without regard to tactical occupational experience or aspirations. As such, it is possible that this sample failed to
represent certain characteristics of individuals likely to pursue such careers. Second, as has been noted by other researchers, an individual's behavior in response to standardized FMS™ instructions is not necessarily a reflection of his/her preferred technique. To the extent that the latter is a better indicator of movement quality, the FMS™ may be limited in its ability to capture this quantity.

CONCLUSION
In conclusion, the results of this study support previously observed increases in the validity of clinically rated movement as a predictor of tactical athlete performance outcomes, specifically when movement quality is rated in conjunction with external loading. Clinicians and recruiters might consider screening for performance-relevant movement dysfunction using adjunct weight. Future research should focus on refining testing methods to increase feasibility and information gained, as well as identifying modifiable factors that best explain this relationship.

REFERENCES
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ABSTRACT

Background: Traditionally, shoulder isometries are introduced in the early stages of shoulder rehabilitation. A patient's isometric torque output is based on a subjective perception of force generation. By utilizing elastic resistance elongation (strain) to standardize force output, clinicians could prescribe shoulder therapeutic isometrics based on % maximum voluntary contraction (%MVC).

Purpose/Hypothesis: The purpose of this study was to measure electromyographic (EMG) activity and determine the %MVC during shoulder flexion, external rotation and abduction isometrics at varying lengths of TheraBand® elastic resistance. It was hypothesized that increased elongation of progressive resistance bands would proportionately increase the %MVC of the shoulder musculature.

Study Design: Laboratory design using healthy subjects.

Methods: Eight healthy subjects (16 shoulders) (5 females, 3 males; avg. age 29.2) were tested. Surface EMG electrodes were placed over the anterior deltoid, middle deltoid, and infraspinatus muscles. A force transducer was anchored to a stable surface with its corresponding end in series with an extremity strap securely holding the elastic band. Subjects were asked to maintain shoulder position for the proper isometric contraction (flexion, abduction and external rotation) while taking incremental steps away from the anchored elastic resistance, to the beat of a metronome to clearly marked distances on the floor (50, 100, 150, 200 and 250% of band elongation). This was repeated with yellow, red, green, and blue TheraBand® resistance levels. Maximum voluntary contractions for both force and EMG were collected for each subject in all three test positions. EMG data were normalized and expressed as a %MVC.

Results: For external rotation and flexion, the infraspinatus and anterior deltoid activity increased with band elongation (p<0.01) and progressive colors (p<0.01). The increases in EMG activity with elongation plateaued with the yellow and red bands but continued to increase with the green and blue bands (p<0.01). The increase in infraspinatus and anterior deltoid EMG activity with progressive band color was more apparent for green and blue bands compared with yellow and red band (p<0.01). For the abduction exercise, middle deltoid activity increased with band elongation (p<0.01) and progressive color (p<0.01). In all three exercises, there was an increase in force exerted by the band with increasing length and band color (p<0.001). However, while there were clear increases in force from red to green to blue, there was no difference in force between yellow and red regardless of elongation (p<0.01).

Conclusion: Isometric flexion, external rotation and abduction muscle activity can be accurately prescribed clinically by adjusting the elongation and resistance associated with progressive colors of resistance bands.

Level of Evidence: 3

Key words: Elastic resistance, isometric exercise, electromyography

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INTRODUCTION
Rehabilitation programs for various shoulder conditions such as rotator cuff repair, stabilization procedures and glenohumeral impingement, emphasize the importance of a progressive rotator cuff strengthening program. Several authors have documented the electromyographic (EMG) activity of the glenohumeral musculature during common therapeutic shoulder exercises. Rehabilitation guidelines for glenohumeral pathologies are typically divided into multiple phases. Within each phase there is a gradual progression of rotator cuff loading based on muscle activation during specific exercises. These programs progress from early isometric exercises to more advanced isotonic exercises in an effort to return the patient to full function. Isometric exercises are regularly implemented by physical therapists for rehabilitation because they can often provide a controllable and safe training stimulus for patients with limited range of motion. The challenge with performing these early-stage isometric exercises is the ability of the patient to accurately estimate the force being used to complete an exercise. The reported force production may be influenced by the sincerity, motivation and pain level of the patient. A person’s ability to continually reproduce a target muscle contraction, regardless if it is maximal or submaximal, is inconsistent. The biomechanical factors that determine muscle force include muscle length, shortening velocity, activation history and current activation. Patients will typically utilize their sense of “effort” rather than their sense of “force” when trying to produce a submaximal contraction. Patients’ perceptions of their effort may not always correlate with the force that they are actually producing. Therefore, it is proposed that using an active isometric technique with elastic resistance can assist in accurately predicting what percent of maximum voluntary contraction (%MVC) will be produced during isometric flexion, abduction, and external rotation of the upper extremity.

Actual force production and muscle activation, as measured by EMG levels using elastic resistance during isometrics, has not been described and needs to be examined. The purpose of this study was to measure EMG activity and %MVC during shoulder flexion, external rotation and abduction isometrics at varying lengths of consecutive resistance levels of elastic resistance. It was hypothesized that an increased elongation of progressive resistance bands would proportionately increase the %MVC of the shoulder musculature.

METHODS
Participants
Eight healthy participants (16 shoulders: 6 males and 2 females; avg age 29.2) volunteered to participate in EMG testing of the glenohumeral joint during reactive isometric exercises. Participants were excluded if they had a history of shoulder injury within one year or presented with pain during the testing protocol. All participants gave written informed consent. This study was approved by the Lenox Hill Hospital Institutional Review Board.

Testing
Prior to testing, yellow, red, green and blue elastic resistance bands (TheraBand®, Performance Health, Akron, Ohio) were cut to 50cm and pre-stretched 50 times to 100% elongation to pre-condition and develop an initial resting length of the bands. Different colors represent progressive thickness of bands, which result in increasing levels of resistance. The elastic resistance bands were attached to a TheraBand® extremity strap at one end and secured to a stable surface with an in-line force transducer (Kistler Instrument Corp, Amherst, NY). Following skin prep (shaving, if necessary, skin abrasion and cleaning with alcohol), circular bipolar Ag-AgCl surface electrodes (Noraxon Dual Electrodes, Noraxon USA, Scottsdale, Arizona; diameter, 1 cm; interelectrode distance, 2 cm) were applied bilaterally on the anterior deltoid, middle deltoid and infraspinatus muscles according to the recommendations of Perotto. Muscle activity was recorded at 960 Hz using an 8-channel telemetry system with a bandwidth of 10 to 500 Hz (Noraxon Telemyo, Noraxon USA, Scottsdale, Arizona). Participants performed three, five-second MVCs in standing (one minute rest between
contractions) with a force transducer (Kistler Instrument Corp, Amherst, NY) for shoulder flexion (anterior deltoid), shoulder abduction (middle deltoid) and external rotation (infraspinatus). The average of the maximum force produced during each of the three contractions was used as the MVC. For MVC testing for flexion, the participants were placed in approximately 10-20° of shoulder abduction, 0° of shoulder flexion and 0° of elbow extension and was instructed to forward flex their shoulder. For shoulder abduction, the participants were placed in approximately 10-20° of shoulder abduction, 5-10° of shoulder flexion and 0° of elbow extension and instructed to maximally abduct their shoulder. For shoulder external rotation, participants were placed with elbow in 90° of flexion and the shoulder in neutral glenohumeral rotation with a towel roll placed between the humerus and the trunk bringing the shoulder to approximately 10° of shoulder abduction. These positions were chosen to keep in line with the stationary force transducer for consistent measurements during MVC tests and reactive isometric recording. These MVCs were performed on both dominant and non-dominant shoulders to develop % MVCs at each testing position.

Participants were then instructed in the three reactive isometric test positions. For external rotation, participants were placed with elbow in 90° of flexion and the shoulder in neutral glenohumeral rotation with a towel roll placed between the elbow and the trunk bringing the shoulder to approximately 10° of shoulder abduction, to help ensure the participant maintained the test position. Participants were fitted with an extremity strap around the wrist for all isometric test positions. Participants were then instructed to step out laterally to clearly identified distances on the floor of 50%, 100%, 150%, 200% and 250% elongation (i.e., each being that percentage greater than the resting length) of the elastic band. Participants ensured they were stepping out the correct distance and maintaining the appropriate shoulder positioning by holding a laser pointer in their test hand that pointed towards the percent elongation marking on the floor. To test shoulder flexion, participants were placed in approximately 10-20° of shoulder abduction, 0° of shoulder flexion and 0° of elbow extension. To test shoulder abduction, participants were placed in approximately 10-20° of shoulder abduction, 5-10° of shoulder flexion and 0° of elbow extension. (Figure 1) Participants were fitted with an extremity strap around the wrist for all isometric test positions. Participants were then instructed to step out laterally to clearly identified distances on the floor of 50%, 100%, 150%, 200% and 250% elongation (i.e., each being that percentage greater than the resting length) of the elastic band. Participants ensured they were stepping out the correct distance and maintaining the appropriate shoulder positioning by holding a laser pointer in their test hand that pointed towards the percent elongation marking on the floor. To test shoulder flexion, participants were placed in approximately 10-20° of shoulder abduction, 0° of shoulder flexion and 0° of elbow extension. To test shoulder abduction, participants were placed in approximately 10-20° of shoulder abduction, 5-10° of shoulder flexion and 0° of elbow extension. To test shoulder external rotation, participants were placed with elbow in 90° of flexion and the shoulder in neutral glenohumeral rotation with a towel roll placed between the humerus and the trunk bringing the shoulder to approximately 10° of shoulder abduction. These positions were chosen to keep in line with the stationary force transducer for consistent measurements during MVC tests and reactive isometric recording. These MVCs were performed on both dominant and non-dominant shoulders to develop % MVCs at each testing position.

Participants were then instructed in the three reactive isometric test positions. For external rotation, participants were placed with elbow in 90° of flexion and the shoulder in neutral glenohumeral rotation with a towel roll placed between the elbow and the trunk bringing the shoulder to approximately 10° of shoulder abduction, to help ensure the participant maintained the test position. Participants were fitted with an extremity strap around the wrist for all isometric test positions. Participants were then instructed to step out laterally to clearly identified distances on the floor of 50%, 100%, 150%, 200% and 250% elongation (i.e., each being that percentage greater than the resting length) of the elastic band. Participants ensured they were stepping out the correct distance and maintaining the appropriate shoulder positioning by holding a laser pointer in their test hand that pointed towards the percent elongation marking on the floor. To test shoulder flexion, participants were placed in approximately 10-20° of shoulder abduction, 0° of shoulder flexion and 0° of elbow extension. To test shoulder abduction, participants were placed in approximately 10-20° of shoulder abduction, 5-10° of shoulder flexion and 0° of elbow extension. (Figure 2) Participants were placed in 10-20° of abduction to prevent any soft tissue between the thorax and humerus from interfering with the position. Participants then stepped anteriorly to each of the five elongation positions, resisting the posterior force of the elastic resistance. Once again, participants held a laser pointer to ensure elongation distances were consistent with each step. To test shoulder abduction, participants were also placed in approximately 10-20° of shoulder abduction, 5-10° of shoulder flexion and 0° of elbow extension. (Figure 3) Participants were placed into 5-10° flexion to clear any abdominal or hip soft tissue that could impede the elastic resistance band. Participants then stepped laterally to each of the five elongation positions, resisting the medial directed force of the elastic resistance. Subjects performed these five step distances sequentially from 50% to 250% stopping at each percent elongation position for approximately 3-4 seconds using a metronome. The metronome pace was set at 12 beats per minute to allow for enough contraction time at each elongation without risking...
increased fatigue and loss of proper positioning. All three of these test positions were randomly ordered and performed with the yellow, red, green, and blue elastic resistance, also in random order.

**Data Analysis**
All EMG data were rectified and smoothed using a root mean square process with a 50-millisecond smoothing window. The maximum value for each contraction was used for analysis. Additionally, all data from the tested exercises were normalized and are presented as %MVC.

For each exercise, data were analyzed using repeated-measures ANOVA to examine the effects of arm side (dominant vs. non-dominant), band elongation (five percentages) and band resistance (four colors) on the primary muscle activated for that exercise: the infraspinatus for isometric external rotation, the anterior deltoid for isometric flexion and the middle deltoid for isometric abduction. Statistical significance was set at $p < 0.05$.

**RESULTS**
Initial analysis showed no effect of side on any muscle activity or force measurement ($p = 0.155$); therefore, dominant and non-dominant arms were grouped together for purposes of analysis. The % MVC for each position and resistance in flexion, external rotation and abduction are listed in the Appendix. Most notable is the change of %MVC in each position from 50% elongation in the yellow to 250% elongation using the blue elastic resistance. Anterior deltoid %MVC increased from $11.2 \pm 1.3\%$ at 50% elongation of yellow to $26.3 \pm 2.3\%$ at 250% elongation of blue. Infraspinatus %MVC increased from $16.2 \pm 2.1\%$ at 50% elongation of yellow to $29.5 \pm 5\%$ at 250% elongation of blue. Middle deltoid %MVC increased from $22.5 \pm 2.7\%$ at 50% elongation of yellow to $36.7 \pm 4.5\%$ at 250% elongation of blue.

For external rotation (Figure 4a) and flexion exercises (Figures 5a and 5b), the infraspinatus and anterior deltoid activity increased with elongation ($p < 0.01$).
and progressive band color ($p<0.01$). The increases in EMG activity with elongation plateaued with the yellow and red bands, but continued to increase with the green and blue bands ($p<0.01$). Additionally, the increase in infraspinatus (Figure 5a) and anterior deltoid (Figures 5a and 5b) EMG activity with progressive band color was more apparent for green and blue bands compared with yellow and red bands ($p<0.01$). For the abduction exercise, middle deltoid activity (Figure 6a) increased with elongation ($P<0.01$) and progressive band color ($p<0.01$). In all three exercises, there was an increase in band force (Figures 4a, 4b, and 4c) with increasing elongation and progressive color ($p<0.001$). However, while there were clear increases in force production from red to green to blue, there was no difference in force production between yellow and red regardless of percent elongation ($p<0.01$).

**DISCUSSION**

This study offers insight into the utilization of elastic resistance in prescribing reactive isometrics for
shoulder rehabilitation. The force exerted by elastic resistance depends on percentage of elongation. In work by Page et al., the slope of the force-elongation curve of elastic bands varies with changes in the thickness of elastic material; specifically, the force-elongation slope of progressive colors slightly increases with increasing thickness. Because elastic resistance is normally prescribed by color, one cannot assume that changes in resistance (color) will cause a standard gradual increase in muscle activation when proceeding from one color resistance to the next in the progression. This concept is clearly seen in the present study as each band was elongated from 50% to 250%. Although the trend shows gradual band force and %MVC increase at each percent elongation, the changes are not of equal percentages based on band color. This study highlights the fact that the greater the resistance supplied by the bands (blue and green) during reactive isometrics, the faster both exerted forces and EMG activity went up, which is consistent with increasing slopes of force-elongation. In contrast, for the bands supplying less resistance (yellow and red) during reactive isometrics, exerted forces and EMG activity increased more slowly.

Previous studies have highlighted the use of elastic resistance during shoulder exercises and shoulder rehabilitation programs. This is the first study on progressive reactive isometric exercise prescription utilizing elastic resistance bands. These findings highlight an increase in muscle activity for each exercise based on band elongation and progressive color. As utilization of isometrics is often limited based on patients’ sincerity, motivation, and pain level, this study provides insight into muscle activity and resistance one can expect to see using reactive isometric resistance exercises with a variety of elastic band resistances.

Clinically, this allows physical therapists to further understand the load placed on shoulder muscles during specific exercises. The data provided offers guidance when prescribing these types of exercises. Clinically, the most important factor is the color (resistance level) of the band. The color of the band drives the increased resistance during longer elongations of reactive isometrics. The absence of this effect for the middle deltoid may indicate that the middle deltoid is not as much of a prime mover as was assumed for the abduction isometric exercise, at this range of motion, with the muscles of the rotator cuff potentially working more than expected. Subjectively, subjects indicated that the task became difficult during the higher elongations, particularly for the higher resistance bands; thus, it is logical to assume there is a large degree of co-contraction of agonist muscles while performing these reactive isometrics at higher loads.

Of note is that all exercises produced muscle activity measured as less than 40% MVC, with the vast majority being under 30% MVC. This should be considered when prescribing therapeutic exercises during the early stages of rehabilitation. Many authors recommend exercising at <20% MVC muscle activation during the early stages following rotator cuff repair. Utilization of the yellow, red, and green reactive isometrics for flexion at 250% elongation falls below this 20% MVC threshold for early stages of rehabilitation. Utilization of reactive isometrics for external rotation fall within this <20% threshold for anterior deltoid for yellow and red up to 150% elongation. Abduction reactive isometrics appear to initiate at >20% MVC of the middle deltoid and should be used with caution during the earlier stages of rehabilitation, and reserved for the middle stages of rehabilitation. Dockery et al. have shown that the use of pulleys for “passive motion” can activate the deltoid up to 25% MVC.

This study presents with areas of limitations. It is important to note that these values are in normal, healthy population and should be considered during exercise prescription for patients with shoulder pathology. Patients with pathology may present with an altered neuromuscular firing patterns that may not necessarily reflect that of a non-pathological shoulder. This study utilized surface EMG and it is possible that kinesiologic fine wire EMG may have different results. Standardization of test positions/movements were achieved with floor marking, the use of a laser pointer, and a metronome pace; however, subject movement during testing is often a variable that is difficult to control.

**CONCLUSIONS**

Isometric flexion, external rotation and abduction muscle activity progressively increases when using varied colors of elastic resistance band (increas-
ing resistance by color) and increasing the percent elongation. The higher resistance bands (green and blue) produced forces faster and EMG activity went up faster than in the lower resistance bands (yellow and red). Using varied choices of elastic resistance to increase the muscle activation during isometric exercises is a novel approach that can allow clinicians to accurately prescribe these exercises.

REFERENCES

### Appendix. Percent MVC for each position

#### Anterior Deltoid: Flexion

<table>
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<tr>
<th>% elongation</th>
<th>Yellow</th>
<th>Red</th>
<th>Green</th>
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<tr>
<td>50%</td>
<td>11.2±1.3</td>
<td>11.8±1.5</td>
<td>12.8±1.5</td>
<td>13.7±1.3</td>
</tr>
<tr>
<td>100%</td>
<td>12.6±1.3</td>
<td>12.9±1.5</td>
<td>15±1.4</td>
<td>16.8±1.5</td>
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<td>150%</td>
<td>14.1±1.2</td>
<td>15±1.6</td>
<td>15.4±1.6</td>
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<tr>
<td>250%</td>
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<td>15.9±1.5</td>
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#### Infraspinatus: External Rotation

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<td>50%</td>
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#### Lateral Deltoid: Abduction

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<td>50%</td>
<td>22.5±2.7</td>
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<td>100%</td>
<td>24.2±2.8</td>
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<td>28.7±3.9</td>
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ABSTRACT

Background: Conventional therapeutic exercise programs are commonly used to treat patients with scapular dyskinesis. There are no studies that have examined traditional therapeutic exercise programs with the addition of remote triggered electrical stimulation (ES) to affect the position of the scapula (using spine to scapular border distance as a reference point) during the performance of exercises that have lower upper trapezius (UT) to lower trapezius (LT) ratio exercises.

Purpose: The purpose of this pilot study was to compare scapular position after performance of three low UT/LT ratio therapeutic exercises in two conditions, electrical stimulation (ESTherex) and sham electrical stimulation (ShamTherex) in asymptomatic persons who were positive for scapular dyskinesis.

Study Design: Randomized trial, single-blinded

Methods: Eleven asymptomatic university students representing 15 scapulae with a positive Scapular Dyskinesis Test were recruited as subjects. Participants were randomized into exercise and electrical stimulation (ESTherex) or exercise and sham electrical stimulation (ShamTherex). Subjects performed side-lying shoulder external rotation and flexion, and prone horizontal abduction with external rotation in both conditions. Scapular position was assessed during active abduction at four angles before and after performance of these exercises.

Results: There were no significant differences in scapula to spine distance between ESTherex and ShamTherex groups at 0, 45, 90 and 120 degrees of shoulder abduction. A between group difference (ESTherex and ShamTherex) approached significance at 45 degrees (p = 0.089, CI = -0.152 to 1.88 cm) with the post mean measurement of the ShamTherex group (6.44 cm) greater than the post mean measurement of the ESTherex group (5.57 cm). The ESTherex showed a significant pre-to-post mean within group improvement in spine to scapula distance at 120 degrees (mean 2.76 cm, t = 4.89, p = .003).

Conclusions: Electrical stimulation with exercises for scapular dyskinesis showed improvements in spine to scapula distance at 120 degrees of shoulder abduction.

Level of evidence: Therapy, level 1b

Key words: Electrical stimulation, lower trapezius, scapular dyskinesis,

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BACKGROUND
The scapula and the shoulder are a highly interconnected functional unit with lifetime prevalence estimates of shoulder pain, although imprecise, due to varying degrees of motion loss and symptom duration, that range from 6.7% to 66.7% for the general population. Because the scapula and shoulder function as a unit, a change in normal kinematics of either will result in aberrant shoulder complex mechanics, termed scapular dyskinesis. Aberrant shoulder complex mechanics result in an increased risk for upper extremity range of motion limitations, upper extremity deficits, or upper quarter pain syndromes. For example, over activation of the upper trapezius (UT) in conjunction with delayed activation of the lower trapezius (LT) results in limited posterior tilt of the scapula. Limited posterior scapular tilt has been postulated to lead to a loss of acromial elevation that may predispose an individual to impingement. A systematic review by Kibler et al. links changes in scapular kinematics during arm elevation to a change in glenoid angle that creates an increased risk of shoulder instability. Shoulder instability and impingement are two of many potential shoulder pain syndromes that may result from altered scapular kinematics.

Scapular dyskinesis (defined as altered scapular motion and position) can be a precursor to an abnormal relationship between the glenohumeral joint and the scapula during movement, and it is therefore critical that dyskinesis be addressed. Dyskinesis describes aberrant scapular position at rest, such as winging of the scapula (excessive prominence of the medial scapular border) and a deviation from normal scapular motion during arm elevation manifesting as a lack of smooth coordinated movement. For example, an individual with observable shoulder shrugging during arm elevation is indicative of lack of coordination between the upper, middle and lower trapezius muscles. Alternatively, Kibler defines a Type II pattern of scapular dyskinesis (Scapular Dyskinesis Classification System) as the presence of a prominent medial scapular border which is most evident during eccentric lowering of the humerus creating rapid downward rotation of the scapula during arm lowering. Excessive shoulder shrugging and rapid downward rotation of the scapula during arm lowering, demonstrate uncoordinated scapular movement, described as scapular dyskinesis.

It is common for physical therapists to treat patients with shoulder pain and scapular dyskinesis. Treatment techniques to address dyskinesis include manual neuromuscular facilitation, tactile cueing, visual feedback, electrical stimulation, supervised exercise, mobilization, strengthening, electromyography, and other interventions.

RESEARCH INCONSISTENCIES REGARDING SCAPULAR DYSKINESIS
Studies linking shoulder pathology and scapular dyskinesis have shown contradictory findings. One example is the inconsistent recruitment timing of scapular muscles noted in a systematic review by Struyf et al. In this systematic review electromyographic studies were used for assessment of scapular patterns in patients with impingement and glenohumeral (GH) instability, compared to healthy controls. Regardless of shoulder pathology (impingement or GH instability) findings were conflicting with regard to recruitment of scapular musculature. Of the six studies that assessed EMG in patients with impingement, three reported increased recruitment of the UT, while three showed no difference in UT activity when compared to healthy controls. Furthermore, of the two studies that compared EMG in the UT of those with and without GH instability, results were also conflicting. One study showed increased UT activity while the other study found no difference in UT activity in individuals with instability compared to healthy controls. Lack of consensus regarding the combined behavior of muscle recruitment and timing, in the treatment of impingement and glenohumeral instability, leave a gap in the literature that can lead to clinical decisions guided by experience rather than evidence. Based on the findings from the systematic review, Struyf et al., recommend assessing and addressing individual motor pattern deficits.

LOWER TRAPEZIUS ROLE IN SCAPULAR DYSKINESIS
One motor pattern deficit noted in scapular dyskinesis is an over active UT combined with an under active LT. Seitz et al. used rehabilitative ultrasound imaging to assess differences in LT muscle thickness in persons with and without scapular dyskinesis.
increased in persons with scapular dyskinesis compared to individuals without dyskinesis. According to the researchers, this change in thickness can be associated with abnormal scapular muscle contractile behavior because of weakness or delayed timing of the muscle. The same trend did not occur when thickness of the serratus anterior muscle was assessed in persons with and without dyskinesis.26

Cools et al.27 used EMG to identify three exercises that address this type of scapular dyskinesis by identifying low UT to high lower and middle trapezius (UT/LT) activation patterns.27 Three exercises were identified: side lying external rotation, side lying shoulder flexion (beginning at 90 degrees), and prone horizontal abduction at 90 degrees of abduction. The exercises found to have a low UT/LT ratio address the voluntary muscle recruitment of the LT while minimizing UT firing. These exercises however, do not address the muscle fiber loss from disuse.

MUSCLE BEHAVIOR AND DISUSE ATROPHY RELATED TO LOWER TRAPEZIUS DYSKINESIS

Disuse results in a selective muscle fiber loss.25 When an individual performs voluntary muscle activation, motor fibers are recruited in an asynchronous fixed pattern with the recruitment of slow conducting, slow twitch, fatigue-resistant small muscle fibers (SSFR) before fast conducting, fast twitch, fatigable, large (FFF) muscle fibers. In contrast, when an individual performs high intensity exercise, fast conducting, fast twitch, fatigable muscle fibers are recruited.29,30 When electrical stimulation (ES) is coupled with voluntary muscle contraction the result is the recruitment of all muscle fibers synchronously, regardless of muscle fiber size and speed of conduction.31 Because of the advantage of this coupled mechanism, electrical stimulation may offer a more comprehensive approach in the treatment of muscles that exhibit alteration in recruitment timing that lead to movement dysfunction.

STUDIES ON THE EFFECT OF ELECTRICAL STIMULATION

Four Cochrane systematic reviews have explored the effect of electrical stimulation in rehabilitation. The reviews differ from the current study in the following ways: one review assessed the effect of ES on central nervous system injuries (CNS)22, while the population in the current study had intact central nervous systems; two reviews assessed the effect of ES on orthopedic shoulder pathologies (rotator cuff disease and adhesive capsulitis),33,34 however both of these were applied to address pain and had very different protocols and purposes compared to this study; the final review assessed electrotherapeutics for chronic pain and again, was not applicable to this study.35 To the knowledge of the authors, the application of stimulation in the current study does not appear in the published literature.

Electrical stimulation has resulted in consistent positive outcomes in varied orthopedic and neurologic patient populations.36-39 A systematic review assessing the effect of neuromuscular electrical stimulation (NMES) after anterior cruciate ligament reconstruction reported improved quadriceps strength 16 weeks post operatively with an exercise and NMES condition, compared to exercise alone.40 Authors suggest that peripheral ES changes motor behavior.31,41 Additional examples of the benefit of ES with an exercise program include a study by Scott et al that supported therapeutic ES at the maximum tolerated stimulation intensity for strength improvements in the quadriceps.36 The consistent positive outcomes of ES are also demonstrated in neurologic populations. A 2015 systematic review by Howlett et al. found moderate improvement in walking speed when ES was compared to no intervention and training alone for functional activity improvement following stroke.37 These studies lend support for underlying mechanisms of ES as a treatment, however no studies directly use ES in the manner being explored in the current study.

RESEARCH DEFINING THE PHYSIOLOGICAL EFFECTS OF ELECTRICAL STIMULATION

Although all the effects that ES has on the body are not completely understood, there is clear support for proposed mechanisms. These mechanisms include the following: 1) the effect on central nervous system (CNS) generated frequency pattern41, 2) excitation of potential selective fiber types42, and 3) dose repeatability (e.g. the same motor response
THE EFFECT ON CENTRAL NERVOUS SYSTEM (CNS) GENERATED FREQUENCY PATTERN

With regard to CNS generated frequency patterns, electrical stimulation is known to modulate ascending and descending input to motor systems. Sugawara et al. found increased primary motor cortex motor evoked potentials (MEPs) in the extensor carpi radialis (ECR) when ES was combined with voluntary muscle contraction compared to ES or voluntary contraction alone. The combination of ES and voluntary muscle contraction of the ECR also resulted in decreased MEPs of the flexor carpi radialis when compared to the condition of ES or voluntary contraction alone.31

In addition to increased primary motor cortex excitability of the electrically stimulated muscle groups, ES recruits (whether the individual chooses to or not) muscle fibers that the patient often does not know how to recruit, or is not able to recruit with his or her voluntary muscle contraction alone. These are also the same muscles that therapists spend a lot of time in treatment trying to get the patient to recruit. Therapist facilitation methods not employing ES do not have the same physiological effects as those using ES. Henderson et al. speculate that there is no difference in motor unit recruitment order based on conduction time in response to ES, but that variability of motor unit pool recruitment is dependent upon the stimulation threshold of the peripheral nerve, the location of axon within the nerve and various other axon characteristics such as hyperpolarization following ES.42 Electrical stimulation that assists in repositioning of the scapula may have the potential to address dyskinesis related disuse as could be associated with an elongated and or weakened lower or middle trapezius. For example, Cools et al. report “abnormal recruitment timing” in the middle and lower trapezius in overhead athletes with impingement.14 If a delay in the onset of muscle recruitment is a reflection of stretch weakness and the stretch weakness persists, and it leads to atrophy (as occurs in innervated skeletal muscle with an intact but unused alpha motor neuron),43 and ES may address this weakness peripherally.

SELECTIVE FIBER TYPE ACTIVATION WITH ELECTRICAL STIMULATION

A motor unit refers to a motor neuron and the associated skeletal muscle fibers,44 a shift in fiber type as result of disuse from dyskinesis, may respond more rapidly to ES combined with voluntary contraction than ES or exercise alone. Specifically, SSFR fibers may be more susceptible to disuse atrophic signaling resulting in a shift in muscle fiber ratios.28,45 When there has been a shift in muscle fiber type, as a result of disuse, aging, and/or disease,28 voluntary muscle contraction may be inadequate to address motor pattern deficits. Efficacious treatments for these patient populations are critically important in a fast-paced payer driven healthcare environment. The upper and lower trapezius are made up of different muscle fiber types, which allows for the various functional roles of the trapezius.46 The lower trapezius is predominantly SSFR (Type I) muscle fiber whereas the upper trapezius is comprised of more FFF (Type II) muscle fiber possibly making the entire muscle complex at risk for shifts in muscle fiber type from disuse.47 However, this same varied fiber composition of the upper and lower trapezius make the trapezius a prime candidate for ES to address ill effects of disuse related muscle atrophy.

ELECTRICAL STIMULATION DOSE REPEATABILITY

The introduction of ES to comprehensively address motor pattern deficits, results in electrically induced muscle contractions, which produce a predictable muscle fiber recruitment that is impossible to achieve with therapist facilitated motor cueing or voluntary muscle contraction alone. Because the training effect is consistently replicable, void of therapist expertise, or void of patient motivation, it may be an optimal training condition. In short, ES adds
consistent training conditions (reproducible intervention, recruitment of all muscle fiber types, and regulation at supraspinal levels). When applied to the dyskinetic scapula it provides a non-volitional, repositioning of the scapula, prior, to the patient performing targeted exercise.

The purpose of this pilot study was to compare scapular position after performance of three low UT/LT ratio therapeutic exercises in two conditions, electrical stimulation (ESTherex) and sham electrical stimulation (ShamTherex) in asymptomatic persons who were positive for scapular dyskinesis.

It was hypothesized that the addition of electrical stimulation to the lower trapezius during low UT/LT ratio therapeutic exercise would produce a greater change in scapular to spine measurements compared to sham electrical stimulation condition during the same low UT/LT ratio exercises.

METHODS

Subjects
Subjects were recruited from a sample of convenience comprised of student volunteers recruited from the Department of Physical Therapy at Fresno State University. Subject recruitment included students with any of the following: scapular winging, excessive scapular motion or prominent scapulae. Inclusion criteria included: aged 18 to 35 years with a positive Scapular Dyskinesis Test (SDT). Positive SDT tests were noted by winging or medial border prominence noted visually at rest, lack of smooth coordinated movement (early scapular elevation or shrugging while raising the arm into forward flexion, and/or rapid downward scapular rotation during arm lowering from full flexion). The motion was characterized as dyskinesis as “yes” (presence of deviation or dysrhythmia/asymmetry) or “no” (no dyskinesis) by an orthopedic certified specialist physical therapist with twenty-six years of clinical experience. The subjects were assessed for visual winging of the scapula at rest and during active flexion and abduction following completion of an intake questionnaire.

Subjects meeting any of the following criteria were excluded: non-intact skin or rash in the electrode area, impaired sensation, impaired cognition, ballistic movements, spastic movements, rheumatoid arthritis, osteoporosis, osteoarthritis, fever, flu-like symptoms, current infection, pregnancy, scoliosis, cancer, thoracic outlet syndrome, myelopathy, diagnosis of fibromyalgia, evidence of any upper quadrant orthopedic cervical disorder or pathology, central nervous system involvement, cervical stenosis, cervical thoracic surgery, chronic migraines, fracture, past or current use of corticosteroids. Exclusion criteria were based on an interview and intake questionnaire review by principal investigators. All subjects provided informed consent before participation. The Department Review Board of Fresno State University in Fresno California approved the study. Eleven subjects representing fifteen scapulae were randomized into ESTherex or ShamTherex group.

Measurement Procedures
Thoracic spinous process (between T7-T10) to inferior scapular angle distance was measured with the arm positioned at varying degrees of shoulder abduction, (0, 45, 90, and 120), in standing. Pre-data collection, intra-rater reliability for the manual measures was established (r = .60).

During the manual measurement, the patient stood facing a wall mounted large diagrammed goniometer. A surgical marker was used to mark the center of rotation at the glenohumeral joint as assessed by two physical therapists. The blinded physical therapist (OCS with 26 years of experience) provided palpation of bony landmarks (kneeling/head down position) while a second physical therapist passively placed the subjects arm in the correct position (abduction with external rotation) so that it was aligned with either the 45, 90, or 120 degree marking on the wall goniometer and the subject actively held the arm once aligned correctly with corresponding angle on the wall goniometer. A trained Doctor of Physical Therapy (DPT) student recorded the tape measured SSD distance. The measurement readings were unknown to the orthopedic certified specialist physical therapist who palpated the bony landmarks. Measurements were taken at the beginning of week 1, and the end of weeks 2 and 3.

Exercise: Protocol and Subject Education
The number of treatments, in addition to repetitions and sets of exercises chosen, are those seen in
usual care outpatient physical therapy settings (2x per week, 3-week duration). Three exercises were selected. The exercises included side lying external rotation at 90 degrees (with a towel roll under the distal humerus), side lying forward flexion from 90 degrees to nose-level (at 120-130 degrees of flexion), prone horizontal abduction with external rotation at 90 degrees abduction (Figures 1-3).

The ESTherex group received ES to the lower trapezius triggered by a second physical therapist (with 20 years of experience teaching electrotherapeutics at Fresno State University), using a remote trigger switch to coordinate the ES immediately prior to the patient initiated movement. In order to ascertain optimal scapular retraction and depression from electrical stimulation, the subject’s arm was placed in a manual muscle test position for the LT and given slight resistance so lower trapezius fibers were visualized for proper electrode placement. The electrode placement was slightly adjusted until the optimal scapular retraction and depression was obtained. Once the desired electrode placement was established, the electrode was outlined with a surgical marker for reproducibility between exercise sessions. The frequency and pulse width were 30pps and 250 usec respectively. A pulse with of 250 usec was used to guarantee a fused muscle contraction (however not a strengthening contraction). Rates greater than 30pps were not used to avoid any signs of muscle fatigability. The intensity was set high enough to produce visible scapular pull with appropriate scapular retraction and depression combined. Once set, the intensity was not changed between treatment sessions. The intensity within the intervention group varied between 23 milliamps (mA) and 29 mA. Stimulation intensity was recorded and reproduced on each subsequent treatment session. The comfort of all contractions was confirmed by the subject’s verbal approval. The ESTherex group performed the three exercises with ES. Each exercise was performed three sets of 15 repetitions with a one-minute rest between exercise repetitions. The electrical stimulation was used during clinic exercise sessions only. A biphasic-pulsatile current was used.
The ShamTherex groups received no ES. The machine was turned on only to show the lights change when the remote trigger was pressed. As with the intervention group, the ShamTherex group also received sham ES via remote trigger application by a physical therapist, beginning just prior to patient initiated movement and stopping with cessation of patient voluntary movement.

One educational session, for exercise program instruction and practice, was provided to both groups, prior to beginning the exercise protocol. Participants received home exercise program (HEP) handouts that included pictures of the three exercises and written instructions. Participants also received HEP logs to record HEP compliance. Participants were instructed to perform all exercises at home in the same manner as performed during the intervention sessions (3x15) without the addition of resistance. Both groups were seen for two treatments per week for three weeks after the initial assessment and set-up visit, for a total of 7 sessions. Participants completed exercise logs during the 3-week treatment duration, and provided a self-report of exercise compliance. All participants reported compliance with the HEP (performed 2 additional days outside of the treatment sessions). All but two HEP logs were maintained by participants, and turned in at the end of the treatment trial. The missing two HEP logs were from participants in the ShamTherex group. Two physical therapists performed all interventions with one DPT student to assist set-up and recording of data.

**RESULTS**

With regard to between group comparisons, spine to scapula distance was assessed in 15 scapulae to compare ESTherex to ShamTherex. Independent t-tests indicated no significant differences in spine to scapula distance between ESTherex and ShamTherex at 0, 45, 90 and 120 degrees of shoulder abduction at the end of the six treatment sessions (Table 1). Independent t-tests comparing post-mean differences (ESTherex and ShamTherex) approached a statistically significant difference at 45 (p = .089, CI = -.152 to 1.88 cm) with the post mean measurement of the ShamTherex group (6.44 cm) greater than the post mean measurement of the ESTherex group (5.57 cm) (Table 2).

For purposes of a learning effect, within group differences were also analyzed. A trend was noted within the ShamTherex and ESTherex groups at 0 and 45 degrees when compared to trends seen within each group at 90 and 120 degrees. In other words, the higher abduction angles (90 and 120) showed closer mean spine to scapula distance compared to the lower angles (0 and 45). At 0 and 45 degrees both the ShamTherex and ESTherex spine to scapula mean SSD scores were larger (further from the spine). A similar trend was noted in the mean scores within the ShamTherex group and the ESTherex group at 90 and 120 with the mean score differences being lower in both conditions at the greater abduction angle. Of significance is the pre-post within group difference of the ESTherex group at 120 degrees of abduction. At 120 degrees of abduction, despite the small sample size, there was a statistically significant decrease in means pre-measurement to post-measurement at 120 for the ESTherex group (mean 2.76 cm, t = 4.89, p = .003) (Table 3). This is even more important to note because the ShamTherex group started with 1.73 cm less spine to scapula distance (better positioning) than the ESTherex group at 120 degrees (ShamTherex 8.44 cm and 6.96 cm, ESTherex -10.17 cm and 7.41 cm) (Tables 3 and 4). Although there was not a significant difference in between group, post-test measures, the within group pre-to-post mean changes of the ESTherex group (measured by SSD distances, as an
indicator of greater scapular excursion) exceeded that of the ShamTherex group. Although the ESTherex group initially started with more scapular excursion compared to the ShamTherex group at the same angle, their within group change was significant even though their scapular position started with more excursion than the ShamTherex group at 120.

**DISCUSSION**

No statistically significant between group difference was found between the ESTherex and ShamTherex group in SSD at different degrees of standing shoulder abduction. There was significant spine to scapula change in distance in the ESTherex group at 120 pre-measurement to final post-treatment measurement. Of note, the pre-measurement of 120, the ESTherex scapula to spine distance was further from the spine in comparison to the ShamTherex group, although the difference was not statistically significant. The significant within group effect for the ESTherex group demonstrates a sustained scapular reposition (measurements taken after ES completed). This finding may reflect the improvement in resting muscle state associated with the addition of electrical stimulation to voluntary drive.49,50 The same within group effect was not seen in the ShamTherex group. In order to understand the meaning of this within group effect, it will be necessary in subsequent studies to not only look at SSD change but to add clinical measures for pain and function in clients with shoulder pain in the presence of dyskinesis, in order to truly understand

---

**Table 2. Independent Samples T Test ESTherex and ShamTherex Post Mean Differences**

<table>
<thead>
<tr>
<th>Shoulder Angle</th>
<th>t</th>
<th>Z –tailed</th>
<th>Mean Difference</th>
<th>Std. Error</th>
<th>Lower</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre0</td>
<td>1.034</td>
<td>.320</td>
<td>.66607</td>
<td>.64439</td>
<td>-.7270</td>
<td>2.058</td>
</tr>
<tr>
<td>Post 0</td>
<td>1.517</td>
<td>.153</td>
<td>.75000</td>
<td>.49434</td>
<td>-.3179</td>
<td>1.812</td>
</tr>
<tr>
<td>Pre 45</td>
<td>1.289</td>
<td>.220</td>
<td>.90179</td>
<td>.69935</td>
<td>-.6091</td>
<td>2.413</td>
</tr>
<tr>
<td>Post 45</td>
<td>1.838</td>
<td>.089</td>
<td>.86607</td>
<td>.47114</td>
<td>-.1518</td>
<td>1.884</td>
</tr>
<tr>
<td>Pre 90</td>
<td>.639</td>
<td>.534</td>
<td>.51964</td>
<td>.81271</td>
<td>-1.236</td>
<td>2.275</td>
</tr>
<tr>
<td>Post 90</td>
<td>-.902</td>
<td>.383</td>
<td>-.51607</td>
<td>.57207</td>
<td>-1.752</td>
<td>.7198</td>
</tr>
<tr>
<td>Pre 120</td>
<td>-1.451</td>
<td>.171</td>
<td>-1.7339</td>
<td>1.1951</td>
<td>-4.316</td>
<td>.8478</td>
</tr>
<tr>
<td>Post 120</td>
<td>-.625</td>
<td>.543</td>
<td>-4.5179</td>
<td>.72239</td>
<td>-2.012</td>
<td>1.109</td>
</tr>
</tbody>
</table>

*Inferior medial scapular angle to spine distance (T7-T10) in centimeters

Note: No statistically significant difference between ESTherex (intervention) & ShamTherex (control) group scapula to spine distance (SSD) in centimeters.

**Table 3. Paired Samples T Test ESTherex (post mean scores)**

<table>
<thead>
<tr>
<th>Pair No.</th>
<th>Pair angle</th>
<th>Mean</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>Sig (t-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>pre0-post0</td>
<td>-.0286</td>
<td>-1.115</td>
<td>1.057</td>
<td>-.064</td>
</tr>
<tr>
<td>Pair 2</td>
<td>pre45-post45</td>
<td>-.0857</td>
<td>-1.003</td>
<td>.8321</td>
<td>-.229</td>
</tr>
<tr>
<td>Pair 3</td>
<td>pre90-post90</td>
<td>.2143</td>
<td>-.9475</td>
<td>1.376</td>
<td>.451</td>
</tr>
<tr>
<td>Pair 4</td>
<td>pre120-post120</td>
<td>2.757</td>
<td>1.376</td>
<td>4.138</td>
<td>4.88</td>
</tr>
</tbody>
</table>

*Statistically significant difference in pre-measurement to post-measurement within group SSD means

**Table 4. Paired Samples T Test ShamTherex (post mean scores)**

<table>
<thead>
<tr>
<th>Pair No.</th>
<th>Pair angle</th>
<th>Mean</th>
<th>t</th>
<th>Sig (t-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>Pre0-post0</td>
<td>-.11250</td>
<td>-.348</td>
<td>.738</td>
</tr>
<tr>
<td>Pair 2</td>
<td>Pre45-post45</td>
<td>-.05000</td>
<td>-.101</td>
<td>.922</td>
</tr>
<tr>
<td>Pair 3</td>
<td>Pre90-post90</td>
<td>1.2500</td>
<td>1.754</td>
<td>.123</td>
</tr>
<tr>
<td>Pair 4</td>
<td>Pre120-post120</td>
<td>1.4750</td>
<td>2.220</td>
<td>.062</td>
</tr>
</tbody>
</table>
the implication of a SSD change. However, because these subjects were positive for dyskinesis but not symptomatic for pain, this could not be assessed during this pilot study.

The absence of a between group effect may be explained by low power in this small pilot sample. Because the intervention specifically addressed LT activation via the addition of ES, the finding that the ESTherex group showed the most improvement at 120 degrees (when the lower trapezius would be most active) may indicate a change in motor pattern. However, this cannot be construed from the one significant outcome of this limited sample population. While both groups (ESTherex and ShamTherex) did not show improvements at 0 and 45, within group changes in SSD were observed from initial to final measurement at 90 and 120; although the finding at 90 degrees was not statistically significant. This is consistent with typical firing patterns seen in the lower trapezius.

The other finding that may be notable and will require further research, is the between group statistic at 45 degrees of abduction (p = 0.089). This finding at 45 degrees abduction, although not significant, in spite of the small sample size, may suggest an improvement in the starting position of the scapula for the ESTherex group. Borsa et al. reported that the scapula downwardly rotates prior to humeral elevation 0 to 30 degrees. Since all scapulae in the study were dyskinetic, a larger sample may change this non-significant observation and answer the question regarding scapular set position prior to elevation in dyskinetic scapulae.

Another important consideration is firing behavior of the LT. Lower trapezius firing is greatest between humeral elevation angles 90 and 120 degrees, with the largest demand at 120 of elevation. In fact, that is what is noted for the within groups’ mean changes observed at 90 and 120, when increased LT activation would start to affect scapular excursion. The greatest mean difference was seen in the ESTherex group at 120. Based on this, a few things may be occurring. At the most demanding LT position (120), the scapula showed the greatest gains in excursion differences with the addition of ES cueing. This was not the case again, for the ShamTherex group (ESTherex 2.76 cm, ShamTherex -1.51 cm). In the case of scapular dyskinesis, as a result of the dis-coordinated recruitment of UT to LT firing, the addition of ES to a targeted exercise program may result in less LT hypoactivity. Although it is important to note that at this time, this idea is only conjecture.

The benefit of adding ES to the LT as an adjunct to three low UT/LT exercises may be multifaceted. Electrical stimulation assists in repositioning of the scapula, ES non-selectively recruits all muscle fiber subtypes, and ES demonstrates positive effects on M1 cortical levels when combined with voluntary muscle contraction.

In this study, investigators observed repositioning of the scapula (increased retraction and depression) as a result of ES cueing. Repositioning of the scapula creates a change in length of the scapular muscles that more closely resembles a non-dyskinetic scapula. This repositioning effect would be applicable for example, in cases such as an elongated LT combined with a shortened pectoralis minor muscle as is seen in scapular protraction. Electrical stimulation facilitated repositioning of the scapula (improved retraction and depression) places the LT and pectoralis minor in a position that more closely approximates non-dyskinetic scapula (in the absence of contrac- ture), compared to scapular protraction alone. This change in position may artificially restore the normal length tension relationships of adjacent soft tissues. Normal length of the scapular muscles can improve the timing of muscle firing, resulting in improved quality of movement, and addresses one aspect of the Scapular Algorithm as proposed by Coops et al. in the treatment of scapular dyskinesia. Additionally, scapular repositioning can create a change in the position of the glenohumeral joint. A change in glenohumeral position will change the soft tissue relationships of the peri-glenoid muscles and ligaments, and in addition, positively affect the scapular muscles.

Electrical stimulation provides a non-selective, synchronous recruitment of muscle fibers that recruits a greater number of muscle fibers than voluntary muscle contraction alone. Electrification recruits all muscle fiber subtypes (type I, IIa, IIx/d, IIb) including oxidative Type I muscle fibers (SSFR) normally recruited in activities of daily
living. If in the case of disuse related dyskinesis, it is the oxidative subtype of muscle fiber that is atrophied, then hypothetically exercise alone should adequately address the muscle fiber imbalance. However, selectivity for muscle atrophy remains a mystery therefore in the absence of understanding the etiology of the disuse, ES may be an essential addition to a comprehensive rehabilitation program.

In addition to possibly reestablishing muscle fiber balance between SSFR fibers and FFF fibers, ES provides input to Type II (FFF) fibers in a standardized and reproducible manner. This type of facilitation is unattainable by conventional physical therapy facilitation techniques alone. When disuse atrophy from aging or disease results in the loss of FFF fibers, ES can assist with the restoration of muscle fiber loss without requiring high levels of exercise or ES induced maximal muscle contractions that can be painful and are likely unachievable in some patients. Not only does ES provide a more complete muscle fiber recruitment; it minimizes practitioner imposed variability by providing a consistent replicable cue. Electrical stimulation produces a highly reproducible positional change of the scapula (with respect to spine to scapular border distance) as a new reference point, which may facilitate improved coordination of upper, middle, and lower trapezius muscle recruitment.

Lower trapezius firing at humeral elevation angles less than 30 degrees of abduction is minimal. In the case of dyskinesis, the potential exists for LT firing at angles less than 30 degrees when setting of the scapula should occur. Premature muscle firing may represent a premature activation of adjacent scapular muscles. Electrical stimulation to the LT at the initiation of shoulder flexion at 90 degrees in sidelying and prone, provides a correctly timed motor cue to the LT to facilitate accurate muscle firing. It is likely that this could carry over into functional positions. Of note, all subjects in the intervention group stated that their scapula felt different after electrical stimulation. No subjects in the control group reported a different feeling in the scapula at any time during the treatment protocol. The participant descriptor word, “different”, was in response to the question posed to all participants at the beginning of each treatment session, “how do you feel?” (asked at the same time HEP logs were checked). Premature firing of the LT (during the scapula setting phase) in dyskinetic scapulae may provide one plausible explanation for the approaching significance between groups at 45 degrees abduction.

Visual inspection of the scapula is a clinically relevant method for assessing scapular dyskinesis. Interestingly however, consistent assessment of the scapula for dyskinesis may not be incorporated into typical physical therapy assessment of the upper quarter. Screening for dyskinesis requires no equipment and can be performed in less than one minute.

LIMITATIONS
The following limitations are noted in this research. This pilot addresses only scapular position as affected by ES of the LT in patients with scapular dyskinesis. It is the recommendation of the authors that continued ES studies should also explore serratus anterior recruitment and/or timing deficits. Second, the use of inferior medial scapular angle to thoracic spinous process distance (SSD), as a predictor of scapular dyskinesis, is an imprecise and overly simplified psychometric that utilizes frontal plane distance to describe impairments that occur in three planes. It is an overly simplified, but clinically useful psychometric to describe static and dynamic positioning of the scapula. SSD was chosen in an attempt to incorporate a tool that is accessible and efficient to administer in busy outpatient settings. The investigators made the assumption that decreased scapula-spine distance indicates less scapular dyskinesis. In the presence of shortened middle trapezius, rhomboid, or levator scapulae muscles, the inferior angle to spinous process distance may also be decreased. Of additional consideration was the limited number of scapulae assessed in this pilot study. Further research with larger and more diverse samples is indicated.

CONCLUSIONS
No statistically significant between group difference was found between the ESTherex and ShamTherex group in SSD at various degrees of shoulder abduction. The significant within group SSD change pre to final post treatment measurement in the ESTherex group at 120 degrees is promising. This finding supports the continued exploration of the effect of ES to the LT combined with low UT/LT ratio exercises in persons with scapular dyskinesis and an increased SSD.
REFERENCES


43. Littell EH. Basic neuroscience for the health professions. Slack; 1990.


ABSTRACT

Background: An observational tennis serve analysis (OTSA) tool was developed using previously established body positions from three-dimensional kinematic motion analysis studies. These positions, defined as nodes, have been associated with efficient force production and minimal joint loading. However, the tool has yet to be examined scientifically.

Purpose: The primary purpose of this investigation was to determine the inter-observer reliability for each node between two health care professionals (HCPs) that developed the OTSA, and secondarily to investigate the validity of the OTSA.

Methods: Two separate studies were performed to meet these objectives. An inter-observer reliability study preceded the validity study by examining 28 videos of players serving. Two HCPs graded each video and scored the presence or absence of obtaining each node.

Discriminant validity was determined in 33 tennis players using video taped records of three first serves. Serve mechanics were graded using the OSTA and categorized players into those with good (≥5) and poor (≤4) mechanics. Participants performed a series of field tests to evaluate trunk flexibility, lower extremity and trunk power, and dynamic balance.

Results: The group with good mechanics demonstrated greater backward trunk flexibility (p=0.02), greater rotational power (p=0.02), and higher single leg countermovement jump (p=0.05). Reliability of the OTSA ranged from $K=0.36$ to 1.0, with the majority of all the nodes displaying substantial reliability ($K>0.61$).

Conclusion: This study provides HCPs with a valid and reliable field tool used to assess serve mechanics. Physical characteristics of trunk mobility and power appear to discriminate serve mechanics between players. Future intervention studies are needed to determine if improvement in physical function contribute to improved serve mechanics.

Level of Evidence: 3

Key words: Functional testing, kinematic analysis, tennis serve

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INTRODUCTION
An effective serve is a key component and can be a major weapon for success in tennis. Many coaches and health care professionals (HCPs) would agree that primary outcomes when developing and teaching the serve are to improve performance (specifically serve velocity) and to prevent injury. Since the serve is the shot that initiates the start of each point, and it accounts for 60% of all strokes it is arguably the most important and predominant shot of the service game. The complex sequence of movements involved in the serve along with its repetitive nature makes it one of the most commonly researched strokes in the game of tennis. A player showing true mastery of the stroke is able to utilize the kinetic chain through a sequence of motions that originate at the lower limbs. These lower limb actions are followed by trunk rotation that ultimately leads to upper limb rotation. However, alterations in the kinetic chain during the serve may have implications on injury and performance.

Researchers investigating the biomechanical demands associated with the tennis serve have successfully targeted the threats to serve performance and upper limb loads that contribute to upper extremity injury. Each of these researchers utilized three-dimensional (3D) motion analysis to investigate the kinematics and kinetics that accompany the serve. 3D analysis has been widely accepted by researchers as the gold standard in movement analysis. However this technique cannot be easily utilized on court (outside environment) and is costly and time-consuming for HCPs and coaches who implement screening programs to plan protocols. Consequently, a field-based observational analysis may be more practical for HCPs and coaches to evaluate tennis serve mechanics.

A field-based observational analysis must be quick, easy to use, allow a HCP or coach to provide almost immediate feedback, and demonstrate reliability and validity. With an understanding of the biomechanical demands required during the tennis serve, researchers created a clinically applicable observational tennis serve analysis (OTSA) tool to evaluate the mechanics of the serve. The tool, initially described in 2008, and later updated in 2013 provided a detailed framework of specific positions representing normal mechanics, abnormal mechanics, and potential strategies to improve altered mechanics. The OTSA was refined in 2013 to be performed on the court and to include video, in order to help improve the effectiveness and applicability of the analysis. The analysis assesses key body positions and motions throughout the kinetic chain that have been found to be associated with optimal ball speed and efficient force production for creating maximal energy with minimal energy expenditure. Additionally, these body positions help to mitigate joint loading to protect against injury. These specific body positions and motions have been defined as “nodes” and have been compiled through 3D motion analysis studies. The framework can be used visually to evaluate the presence or absence of the nodes during the service motion.

The investigations reported in this paper were accordingly designed to determine the reliability and validity of the OTSA tool. The primary purpose was to determine the inter-observer reliability for each node between two health care professionals that developed the OTSA. It was hypothesized that the reliability would be greater than 0.41 for the majority of the nine nodes of the OTSA. The secondary purpose was to investigate the validity of the OTSA by determining if a series of field tests to evaluate trunk flexibility and power, lower extremity power, and dynamic balance would discriminate between players with good and poor serve mechanics as assessed by the OTSA. The authors’ hypothesized that players demonstrating good serve mechanics would perform better on a series of musculoskeletal field tests compared to those with poor serve mechanics.

METHODS
Two separate studies were undertaken to meet the objectives of performing a validation and reliability study. In order to be transparent in the methods and for clarity, the studies methods and results sections have been subdivided into two components.

Subjects
Two samples of participants were used to document the reliability and validity of the OTSA. To determine the inter-observer reliability of the OTSA video data from 28 professional women's tennis players were analyzed. All players were actively participating on the professional tour. Players were excluded...
if diagnosed with a neurological disorder, or had a history of fracture and/or surgeries within a year of the video collection. The research team received a waiver of consent from The Lexington Clinic Orthopedic Research Review Board.

To investigate the validity of the OTSA a cross-sectional study was implemented on 33 healthy non-professional tennis players. Player characteristics are detailed in Table 1. Players were considered eligible if they participated in tennis at least once a week (college, high school, or recreational), had a United States Tennis Association National Tennis Rating (USTA NTR), and were not under medical care for a musculoskeletal condition that affected tennis play. Players were excluded if any of the players had been diagnosed with a neurological disorder, or had a history of fractures and/or surgery within the past year. Prior to participation, all players gave informed consent approved by the University of Kentucky Institutional Review Board.

Procedures

**Observational Tennis Serve Analysis (OTSA) Tool**

The Women’s Tennis Association (WTA) in conjunction with the Shoulder Center of Kentucky (Lexington, KY) developed the OTSA as a field-based tool that can be used to assess tennis serve mechanics. The OTSA is divided into nine components, the first eight components are called nodes, and the last component is an assessment of motion. The first eight nodes are evaluated at maximal knee flexion while the last component is assessed during the entire serve motion, and represents the composite motion of the entire serve. Each of the eight nodes and the composite motion are graded separately as present or absent, using specific criteria that define efficient and inefficient mechanics (Table 2). If a node is graded as present a score of one is recorded for that particular node, whereas a node that is graded absent is recorded as zero. A composite score is totaled by taking the sum of the individual nodes, with a maximum score of nine representing excellent mechanics, and a zero representing poor mechanics.

**INTER-OBSERVER RELIABILITY**

A retrospective analysis was performed to determine the inter-observer reliability of the OTSA. Twenty-eight service videos were supplied independently to two observers, an orthopedic surgeon (WBK) and a licensed physiotherapist (BS). Each video contained one service trial from the deuce court during match play. The digital camera was placed at the back corner of the court at approximately 45° angle to the player’s back. The observers were blinded to player name. Both observers were experienced in tennis sports medicine (combined experience of 40 years) and were instrumental in creating the OTSA tool. Each observer independently evaluated each serve, using a standardized scoring sheet. The observers reviewed the videos as much as needed using slow motion and freeze-frame during maximal knee bend. The two observers recorded categorical data for each of the nine components on each player.

**VALIDITY**

Prior to all data collection for the validity portion of this study each player underwent a standardized 10-minute warm-up period that included jogging, lower and upper extremity mobility drills, and no more than 10 practice serves from the deuce court. Following the warm-up, players were asked to perform three of their best first serves. Each service trial was captured using two digital cameras (Panasonic HDC-HS60, Hamburg, Germany). One camera was positioned anteriorly to the participant, 20 feet from the baseline “T” of the court at a 20° angle. The second was positioned posterolaterally to the participant, 14 feet from the baseline “T” of the court at a 45° angle (Figure 1). These two camera positions were chosen as they elicited the best angles for viewing all nine components associated with the OTSA.

### Table 1. Demographic characteristics for players enrolled in validity study

<table>
<thead>
<tr>
<th>Sex</th>
<th>Good Serve Mechanics</th>
<th>Poor Serve Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Female</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>Age*</td>
<td>23 ± 9</td>
<td>38 ± 16</td>
</tr>
<tr>
<td>Body Mass Index*</td>
<td>23 ± 2</td>
<td>24 ± 3</td>
</tr>
<tr>
<td>Arm Length*</td>
<td>0.64 ± 0.08 m</td>
<td>0.57 ± 0.03 m</td>
</tr>
<tr>
<td>USTA Ranking*</td>
<td>6 ± 0.6</td>
<td>4 ± 1.0</td>
</tr>
<tr>
<td>OTSA Composite</td>
<td>6 ± 1</td>
<td>2 ± 1</td>
</tr>
</tbody>
</table>

*Represented with mean ± standard deviation

m = meters

USTA = United States Tennis Association

OTSA = Observational Tennis Serve Analysis
Table 2. *Observational Tennis Serve Analysis Tool Grading Scale*

<table>
<thead>
<tr>
<th>Node 1: Foot</th>
<th>Efficient Mechanics</th>
<th>Inefficient Mechanics</th>
<th>Picture of Good Mechanics</th>
<th>Picture of Bad Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: Back foot stays behind front foot</td>
<td>Bad: Back foot stays in front of front foot</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node 2: Knee</th>
<th>Efficient Mechanics</th>
<th>Inefficient Mechanics</th>
<th>Picture of Good Mechanics</th>
<th>Picture of Bad Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: Both knees to bend greater than 15°</td>
<td>Bad: Both knees bend less than or equal to 15°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node 3: Counterhip Rotation</th>
<th>Efficient Mechanics</th>
<th>Inefficient Mechanics</th>
<th>Picture of Good Mechanics</th>
<th>Picture of Bad Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: The hip on back side is rotating away from the net</td>
<td>Bad: The hip on back side is not rotating away from the net</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: The hip on back side is dropping towards the ground</td>
<td>Bad: The hip on back side is not dropping towards the ground</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node 5: Hip Lean</th>
<th>Efficient Mechanics</th>
<th>Inefficient Mechanics</th>
<th>Picture of Good Mechanics</th>
<th>Picture of Bad Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: The hip on front side is not leaning forward towards the net</td>
<td>Bad: The hip on front side is leaning forward towards the net</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: x-angle describes the relationship between the shoulders and the hips and should be ( \approx ) equal to 30°</td>
<td>Shoulders don’t rotate behind the hips</td>
<td>Bad: the x-angle is less than 30°</td>
<td>Shoulders rotate too far behind the hips</td>
<td>Bad: the x-angle is greater than 30°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node 7: Trunk</th>
<th>Efficient Mechanics</th>
<th>Inefficient Mechanics</th>
<th>Picture of Good Mechanics</th>
<th>Picture of Bad Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good: Trunk rotation around a vertical axis</td>
<td>Bad: No trunk rotation, lateral trunk bending only, lumbar hyperextension, hyper-rotation, or hypo-rotation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
chloride (PVC) pipes were used to create an angle to record trunk flexibility. One PVC pipe (1 meter long) was placed on the ground in between the foot and the knee in the coronal plane. Another PVC pipe was placed behind the players back and between the arms while the hands were placed on the hips. Trunk flexibility was expressed by the direction in which the serving shoulder was moving (backward or forward). For example, backward rotation for a right-handed server was performed by kneeling on the left knee while positioning the right foot in front of the kneeling leg and instructed to rotate the serving arm backwards. Forward flexibility was performed in an exact manner except players were kneeling on the right leg and instructed to rotate the serving arm forwards. Participants were asked to rotate as far as possible without losing balance and maintaining correct posture. The examiner stood behind and above the players and took a snapshot using a digital camera at the end range of motion.

ImageJ, an open source imaging processing system (https://imagej.net) was used to calculate the

<table>
<thead>
<tr>
<th>Table 2. Observational Tennis Serve Analysis Tool Grading Scale (continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 8: Arm</td>
</tr>
<tr>
<td>Efficient Mechanics:</td>
</tr>
<tr>
<td>Good: Shoulder in line with the plane of scapula</td>
</tr>
<tr>
<td>Picture of Good Mechanics:</td>
</tr>
<tr>
<td>Inefficient Mechanics:</td>
</tr>
<tr>
<td>Bad: Hypercocking – shoulder behind plane of scapula</td>
</tr>
<tr>
<td>Picture of Bad Mechanics:</td>
</tr>
</tbody>
</table>

Assessment of Motion 9: Compositive Motion of Kinetic Chain

| Good: Use knee flexion and back leg drive to maximize ground reaction forces that push the body upward from the cocking position into ball impact |
| Bad: Use trunk muscles to pull the trunk and arm from cocking into ball impact |

*Note: Evaluate nodes 1-8 at maximum knee bend. Composite motion of kinetic chain should be evaluated throughout entire motion.

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TRUNK FLEXIBILITY

A variation of Aragon et al\textsuperscript{20} trunk rotation flexibility measure was adopted for this study. Two polyvinyl chloride (PVC) pipes were used to create an angle to record trunk flexibility. One PVC pipe (1 meter long) was placed on the ground in between the foot and the knee in the coronal plane. Another PVC pipe was placed behind the players back and between the arms while the hands were placed on the hips. Trunk flexibility was expressed by the direction in which the serving shoulder was moving (backward or forward). For example, backward rotation for a right-handed server was performed by kneeling on the left knee while positioning the right foot in front of the kneeling leg and instructed to rotate the serving arm backwards. Forward flexibility was performed in an exact manner except players were kneeling on the right leg and instructed to rotate the serving arm forwards. Participants were asked to rotate as far as possible without losing balance and maintaining correct posture. The examiner stood behind and above the players and took a snapshot using a digital camera at the end range of motion.

ImageJ, an open source imaging processing system (https://imagej.net) was used to calculate the
angle of rotation using the PVC pipes as landmarks (Figure 2). The averages of three trials for both backward and forward flexibility were used for data analysis. Total arc of motion was calculated by adding backward and forward rotation angles together for each subject. Excellent inter-rater reliability of the measurements were established prior to starting data collection using the data of six participants for both forward (ICC = 0.99, 95%CI = 0.93-1.00) and backward flexibility (ICC = 0.99, 95%CI = 0.99-1.00).

**TRUNK ROTATIONAL POWER**

The field test of Cowley and Swensen for the power component of core stability was modified so that in addition to measuring the distance the medicine ball traveled, power was calculated by power (Watts) = (force x distance)/time. Players’ arm lengths were measured bilaterally from the tip of the acromion process to the radial styloid process. Each player was instructed to sit with both feet flat on the ground shoulder width apart. The elbows were extended and supinated, and the 5th digits from the left and the right hands were touching. A 2.72 kg medicine ball was placed in the participants’ hands. Each player was then instructed to maintain a flat back and to lower the torso to a 45° hip angle; this position was confirmed with a standard goniometer. Lastly, players were asked to rotate the trunk to approximately 90° so the serving arm moved backwards (Figure 3a), and to perform an explosive contraction of the core musculature using the arms as levers to project the medicine ball to the opposite side of rotation. The medicine ball was released from the hands when the player reached the opposite knee (Figure 3b). Participants were given up to five practice trials. A one to two minute rest period was given between practice and actual testing. The average of the three trials were used for data analysis.

**Table 3. Intra-observer reliability performed by one experienced sports medicine professional evaluating the service videos of 13 professional players**

<table>
<thead>
<tr>
<th>Node</th>
<th>Description</th>
<th>Kappa Coefficient</th>
<th>Level of Agreement (%)</th>
<th>95% Confidence Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>Foot Position</td>
<td>1.0a</td>
<td>100</td>
<td>1.00, 1.00</td>
</tr>
<tr>
<td>Node 2</td>
<td>Knee Position</td>
<td>0.75b</td>
<td>92</td>
<td>0.29, 1.21</td>
</tr>
<tr>
<td>Node 3</td>
<td>Counterhip Rotation</td>
<td>0.63b</td>
<td>92</td>
<td>-0.07, 1.33</td>
</tr>
<tr>
<td>Node 4</td>
<td>Posterior Hip Tilt</td>
<td>0.75b</td>
<td>92</td>
<td>0.29, 1.21</td>
</tr>
<tr>
<td>Node 5</td>
<td>Hip Lean</td>
<td>0.83c</td>
<td>92</td>
<td>0.51, 1.15</td>
</tr>
<tr>
<td>Node 6</td>
<td>X-Angle</td>
<td>0.64c</td>
<td>85</td>
<td>0.20, 1.10</td>
</tr>
<tr>
<td>Node 7</td>
<td>Trunk Position</td>
<td>1.0a</td>
<td>100</td>
<td>1.00, 1.00</td>
</tr>
<tr>
<td>Node 8</td>
<td>Arm Position</td>
<td>0.75b</td>
<td>92</td>
<td>0.29, 1.21</td>
</tr>
<tr>
<td>Assessment</td>
<td>Composite Motion of Motion 9</td>
<td>0.58c</td>
<td>85</td>
<td>0.05, 1.11</td>
</tr>
</tbody>
</table>

*Indicates almost perfect level of agreement (≥ 0.81)

*bIndicates substantial level of agreement (0.61 to 0.80)

*cIndicates moderate level of agreement (0.41-0.60)
COUNTERMOVEMENT VERTICAL JUMP

Lower extremity power was assessed with double and single leg CMJ. All players were asked to maintain an upright position followed by a quick crouching action to propel the body into a maximal vertical jump. The participants were instructed to jump vertically as high as possible while keeping the legs straight in the air. The use of the arms to reach as high as possible was permitted as part of the movement. A familiarization period consisted of up to three practice jumps for both the double and single CMJ. A rest period of two minutes was given in between double and single legged jumps. The single leg jump was performed on the dominant leg (defined as the ipsilateral leg as serving arm).

A standard video camera was placed anteriorly to each player so the entire movement was filmed (medicine ball release to ground contact). All videos were uploaded and analyzed using video motion-analysis software (Dartfish 8 ProSuite; Dartfish, Fribourg, Switzerland) where distance in meters and time in seconds were calculated. The video camera was calibrated using a reference distance prior to the task. A meter stick was placed horizontally next to the player to calibrate the video recording of the ball toss. This step was essential in measuring distance within video motion-analysis as it provided a known distance in order to compute the distance each person threw. The start time of the movement was defined as the point in which the medicine ball crossed over the opposite leg just before release and ended at ball contact with the ground. The duration of the event was used to calculate power. A member of the research team used these same time points to measure the distance the medicine ball traveled in meters. The weight of the medicine ball was converted into 26.64 newtons, and represented force, the distance was represented in meters, and the time in seconds. Excellent inter-rater reliability of the measurements was established using the data of six participants for trunk rotational power (ICC = 0.98, 95%CI: 0.90-0.99).
In combination with the reliability statistics, several researchers have suggested the proportion of positive agreement be calculated to provide readers with a clearer understanding of reliability. Furthermore, this proportion should be considered when a kappa paradox is present, in which a low kappa statistic accompanies a high level of observed agreement between observers. When this paradox is present, interpretation of the kappa on its own may not be meaningful, and calculation of the proportion of positive agreement should be generated to interpret the results. The following equation was used to calculate the proportion of positive agreement using the same data within the 2 x 2 contingency tables exported from SPSS when generating Kappa statistics.

\[
P_{\text{pos}} = \frac{2a}{N + a - d}
\]

Where:
- \(N\) = # of observations
- \(a\) = true positive
- \(d\) = true negative

Excellent inter-rater reliability of the measurements was established using the data of six participants for both double leg (ICC = 0.99, 95%CI = 0.98-1.00) and single leg (ICC = .97, 95%CI = 0.80-0.99). The average of the three double leg and single leg CMJs were used for data analysis.

DYNAMIC BALANCE
Dynamic balance was measured using the anterior direction of the Star Excursion Balance Test. Each player was given standardized verbal instructions along with a visual demonstration, followed by four practice trials. While barefoot, the participants then performed three test trails in the anterior direction for each leg. A member of the research team measured leg length on each limb while the participants lay supine. The distance in centimeters (cm) was recorded from the Anterior Superior Iliac Spine to the center of the ipsilateral medial malleolus. Reach distance was normalized to each participant’s limb length by dividing by the players’ leg length (cm) and multiplying by 100. The average normalized percent leg length score among the trials for each stance leg was used for data analysis. Excellent inter-rater reliability of the anterior reach Star Excursion Balance Test has been previously established (ICC = 0.92).

Statistical Analysis
Percentage of observed agreement and kappa (K) coefficients were used to investigate inter-observer reliability for each of the nine components of the OTSA. K was interpreted using the following scale: ≤ 0 = poor agreement, .01-.20 = slight agreement, .21-.40 = fair agreement, .41-.60 = moderate agreement, .61-.80 = substantial agreement, and .81-1 = almost perfect agreement. A final composite score was calculated for each of the 28 players by summing together the individual scores of each of the nine components. To determine the inter-rater reliability of the total composite score, an Intraclass Correlation Coefficient (ICC) was utilized.

The dependent measures from the field tests (trunk flexibility, rotational power/distance, CMJ, and dynamic balance) were analyzed separately using an analysis of covariance (ANCOVA) to determine if physical characteristics would demonstrate differences between those with good and poor serve mechanics. One player from the good serve mechanics group was unable to perform forward trunk flexibility; therefore this player was removed from flexibility analyses (forward, backward, and total motion) leaving 15 players data for statistical analysis in this group. All other analyses used data from all 17 players in the poor mechanics group and 16 players in the good mechanics group. An ANCOVA was utilized to remove bias that may contribute differences present within the two groups (Table 1). Chi square analysis was used to remove bias that may contribute differences present within the two groups (p=0.04), and independent t-test revealed a difference in age between the two groups (p<0.001). Arm length was found to be different between groups (p=0.006). All analyses incorporated sex and age as a covariate to account for group differences. Additionally, arm length was incorporated into trunk
The percentage of observed agreement between the two observers varied by node and is presented in Table 4. The kappa scores ranged from 0.36 to 1.0, and the level of agreement ranged from 78 to 100% agreement. Five out of the nine nodes scored $K > 0.61$. The average composite score for Rater 1 was $7 \pm 2.1$ and Rater 2 was $7 \pm 2.2$. There was excellent inter-observer reliability between the two raters using the composite score ($ICC = 0.90, 95\% CI: 0.847-0.985$). The kappa paradox was present in the other four nodes (2, 5, 7, 8) with lower Kappa scores. The proportions of positive agreement for these four nodes range from 0.57 to 0.96 and are also presented in Table 4.

Validity
Trunk flexibility and power measures discriminated between the two groups (Table 5). Backward trunk flexibility and total arc of motion were significantly greater in those with good mechanics compared to those with poor mechanics when adjusting for age and sex. Similarly, trunk rotational power and distance were greater in those with good mechanics compared to poor mechanics when adjusting for age, sex, and arm length. Dominant single leg CMJ was also greater in those with good mechanics by 10cm. There were no significant differences between groups for forward trunk flexibility, double leg CMJ, or dynamic balance (Table 5).

DISCUSSION
The OTSA was developed using kinematic findings from 3D motion analysis studies. The developers of this tool suggested the analysis might be practical for coaches and HCPs to evaluate serve mechanics in the absence of costly 3D biomechanical equipment. However, the practicality of such a tool cannot be suggested without basic psychometric properties. Therefore, the current study investigated the validity and inter-observer reliability between the two HCPs that helped to create the OTSA. It was hypothesized that players demonstrating good serve mechanics would perform better on a series of musculoskeletal field tests compared to those with poor serve mechanics. The hypothesis was partially supported as five measures were found to differentiate those with good and poor mechanics. Players with good mechanics demonstrated approximately 11° more backward trunk flexibility and 23° more total trunk rotational motion. Those with good serve mechanics generated 46 more watts of trunk rotational power,
had a greater throwing distance on average of two meters (m) during the trunk rotational power test, and jumped an average 10cm higher on the dominant single leg CMJ compared to players with poor mechanics. Additionally, it was hypothesized that the inter-observer reliability would be greater than 0.41 for the majority of the nine nodes. This study supported that hypothesis as 89% of the nodes generated moderate to almost perfect agreement. However, caution must be taken when interpreting the kappa values of the nodes generating fair to moderate agreement, as the kappa paradox was present within these four nodes.

The kappa is “affected by the prevalence of the finding under consideration much like prediction values are affected by the prevalence of the disease under consideration.”\(^{30}\) For example, the low kappa value (0.36) associated with node five presents with a percentage of observed agreement of 89% (two observers in agreement 25 out of 28 observations). This occurred because 24 out of the 25 agreed responses were that players did exhibit forward hip lean, and only one time did the raters agree that the athlete did not exhibit forward hip lean during the serve. Therefore, there is much agreement among the observers, but there is an uneven distribution of observations within the contingency table. With the proportion of positive agreement value reaching near one, (0.94 in this case) it can be interpreted that the decline in kappa is a result of the high prevalence of “yes” responses (24 responses) compared to “no” responses (one response) between the observers.\(^{29}\) The kappa value representing nodes five, seven, and eight seems to be underestimating the true agreement between these two raters providing an additional method to interpreting the data that may help to provide a clearer picture.\(^{29}\)

Results of the present study suggest that trunk flexibility and power capacity of both the trunk and lower extremity are key contributions to good serve mechanics. Tennis researchers have investigated the relationship between rotational trunk kinematics during the serve and serve velocity. Elite players displaying trunk rotation about the anteroposterior and transverse axis early in the service motion had improved serve speeds compared to those demonstrating rotation later in the motion.\(^{1}\) Consistent with the findings of this study, lower handicapped golfers demonstrated 10° more torso flexibility than those with higher handicaps.\(^{34}\) Previous authors have indicated that poor torso flexibility may inhibit the mechanics of the golf swing, specifically the X factor (or x-angle), thus diminishing drive distance and decreasing velocity.\(^{35,36}\) The role of torso rotation has also been demonstr-
In this study, single leg CMJ height on the dominant leg revealed a 10-centimeter difference between the two groups while the double leg CMJ showed no difference between the groups. While this study did not measure lower extremity forces, these findings may suggest that those with good mechanics are able to maximize back leg drive up and through the serve, as this is the basis for proper hip motion and subsequent acceleration. This is consistent with the work of Girard et al,44 who showed elite tennis players activate the dominant leg muscles earlier in the tennis motion than less skilled players, and of Whiteside et al11 who showed elite adult female tennis players to have greater dominant leg triple extension velocities and racquet velocities at impact compared to prepubescent elite players. The importance of this finding is that each leg should be independently evaluated when screening players for potential lower extremity power deficits.

There are several advantages to this type of observational analysis. First, it is portable to practice or tournament sites, and can be implemented by using a standard video camera. Second, it allows coaches and HCPs to easily identify mechanical flaws within the service motion to improve performance and diminish possible injury risk. Third, by specifically demonstrating failures to achieve specific nodes, it can highlight areas for more comprehensive musculoskeletal evaluation, treatment, and conditioning. In turn, coaches and HCPs may evaluate specific body regions that aid in the improvement of the serve technique. With the identification of node deficiencies it may be possible to develop programs to improve mechanics, performance, and ultimately reduce injury risk.

These investigations have limitations. First, serve mechanics and power were not assessed using 3D kinematic and kinetic analysis. However, the protocol used to measure kinematics and power reflects practical field tests. Second, the outcomes of the tennis serves were not recorded. The authors did not document if the three service trials were considered playable points. Future studies should document the outcome of each service trial to combat this limitation. Third, two experienced sports medicine professionals who were involved in the development of the method performed the analysis. Future research is underway to address this specific limitation by incor-
porating more HCPs and tennis coaches that have not developed the OTSA tool into a larger reliability study. Lastly, future research should investigate if a standardized training intervention can improve the mechanics of the tennis serve. Based on the current results, an intervention should likely incorporate trunk flexibility and both trunk and lower extremity interventions as these components were able to differentiate those with good and poor serve mechanics.

CONCLUSION
The OTSA has a high agreement between two experienced observers, indicating good to excellent reliability. This system has the potential to help coaches, players, and HCPs better analyze the tennis serve motion. This study demonstrated that specific physical characteristics can differentiate players with good and poor serve mechanics as defined by the OTSA scores. Specifically, trunk rotation and power capacity of the trunk and lower extremity are key areas that may contribute to poor serve mechanics and may be reasonable starting points to address in interventions that may enhance serve mechanics and performance.

REFERENCES


ABSTRACT

**Background:** General Medical Practitioners (GMP) in Denmark perform clinical examinations of patients with musculoskeletal pain. However, the prevalence proportion of examinations caused by running-related injuries remains unknown.

**Purpose:** The primary purpose of the present study was to estimate the prevalence proportion of consultations in general medical practice caused by running-related injuries. The secondary purpose was to estimate the prevalence proportion of injured runners, who consult their GMP, that are referred to additional examinations or treatments.

**Study Design:** A survey-based study.

**Methods:** An online survey was distributed in October and November 2015 to more than 370 GMPs in Denmark and completed by 27.

**Results:** The median prevalence proportion of consultations caused by running-related injuries in the prior two weeks was 0.80% [25th percentile = 0.00%; 75th percentile = 1.43%]. Ten (37%) GMPs reported to refer between 0-24% of the injured runners to additional examination or treatment, whereas thirteen (48%) of GMPs referred between 25-49% and four (15%) referred 50-74% of injured runners.

**Conclusion:** Although a very small part (<1%) of the GMPs consultations were related to running injuries, this result suggests that injured runners seek advice in the primary health-care system in Denmark. As a consequence, physiotherapists willing to treat runners with running-related injuries may inform the GMPs in their local community about the treatment possibilities they offer. The low response-proportion highlights the challenges recruiting GMPs willing to respond to questionnaires on running-related injuries. It is plausible to assume that the estimates reported in the present study are overestimated owing to selection bias.

**Level of Evidence:** 3

**Key words:** Family medicine, injuries, physiotherapy, running

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INTRODUCTION
Physical activity plays an important role in prevention of lifestyle diseases, which affect large segments of the population and account for comprehensive socioeconomic burden. Therefore, an effort to increase physical activity should be considered a public-health priority. Running has been shown to be a popular form of physical activity among less active people seeking a healthier lifestyle and persistent running practice remains fundamental to obtaining well-established individual and socioeconomic benefits.

Running-related injuries (RRIs) are a common problem, since a recent meta-analysis, revealed a weighted incidence rate of 17.8 injuries (95% confidence interval [CI] 16.7;19.1) per 1,000 hours of running in novice runners and 7.7 (95% CI 6.9;8.7) per 1,000 hours of running in recreational runners. Patello-femoral pain, iliotibial band syndrome, medial tibial stress syndrome, Achilles tendinopathy and plantar fasciitis are running injuries commonly diagnosed by health-care professionals.

General Medical Practitioners (GMPs) are primary care providers and are usually the first point of contact for a runner in the health-care system. GMPs in Denmark use the International Classification of Primary Care 2 (ICPC-2) coding system to document the health issues of each patient. An ICPC-2 code consists of a letter and two numbers, and registers musculoskeletal problems by anatomical region, e.g. L15 symptoms/complaints knee or L77 ankle sprain. In Central Denmark Region, 14.5% of the consultations performed by GMPs in 2009 were reported as musculoskeletal problems. The causative factors for these musculoskeletal problems are not registered due to the organization of the ICPC-2 coding system. As a consequence, it is impossible to conduct a register-based study to investigate the prevalence proportion of consultations in GMP practices caused by RRIs.

In a study of novice runners participating in a Dutch “Six-week start to run program”, Hespanhol et al. reported a prevalence proportion of 9.6% of the injured runners consulting their GMP. In addition, amongst marathon runners, Van Middelkoop et al. reported a prevalence proportion of 16.4% of the injured runners consulting a GMP because of their RRI. In a study on the Dutch population, Baarveld et al. found 8.6% of sports-related consultations to be due to running/jogging as injury-prone activity. Finally, amongst injured road runners, 24% consulted a GMP. Although interesting, these data do not clarify the prevalence proportion of RRI consultations in general practice. The primary purpose of the present study was to estimate the prevalence proportion of consultations in general medical practice caused by running-related injuries. The secondary purpose was to estimate the prevalence proportion of injured runners, who consult their GMP, that are referred to additional examinations or treatments.

METHODS
Ethics and protection of data
The Scientific committee, North Denmark Region, evaluated the protocol but waived the request for approval because observational studies, according to the Danish law, do not require an ethical approval. The study was approved by the Danish Data Protection Agency (J. nr. 2008-58-0028).

Recruitment of general practitioners
In order to estimate the prevalence proportion of consultations amongst GMPs in Denmark caused by RRI, an online survey was distributed in October and November 2015. To reach as many GMPs as possible, the questionnaire was widely distributed: (i) via the newsletter of NordKAP, an organization that encompasses ~340 GMPs in the North Denmark Region; (ii) GMPs were contacted face-to-face at an annual national conference (Lægedage 2015) held in Copenhagen; (iii) Danish GMPs were contacted by phone and encouraged to respond; (iv) and face-to-face contact in their practices was used to further support participation (Figure 1).

Questionnaire development and pilot testing
Qualitative interviews with runners and GMPs were conducted in advance of constructing the electronic questionnaire. Standardized questionnaire methodology was used to inform the design of the questionnaire. The preliminary questionnaire was pilot tested and modified in two phases in order to analyze the questionnaire comprehensibility and adequacy in achieving targeted data collection goals as defined in
Pilot version 1
Development of questionnaire based on predefined research questions. A thorough process performed in cooperation with a professional expert in questionnaire development in order to secure the optimal sequence of questions together with ideal wording.

Test and evaluation
Feedback interviews with four independent GMPs

Pilot version 2
Suggestions from the four GMPs incorporated.

Content:
- Modification of question regarding the three most frequent RRI diagnoses, due to risk of recall bias
- Exclusion of a question examining the proportion of runners being seen > 3 times per RRI
- Exclusion of two questions examining details of the typical runner seen with RRI in GMP
- Addition of ankle sprain in the eligible category of frequent RRI
- Uniting and regrouping questions regarding diagnostics and treatments of RRI

Definitions:
- Linguistic modifications of the introductory remarks to certain questions
- Reworking of available options of treatments and type of practice.

Test and evaluation
Performed by GMPs

Final Questionnaire
Design optimization and continuous scale questions changed to eligible intervals in aim for increased compliance

Distribution

(i) NordKAP
∼340 asked*
14 fulfilled
(ii) GMP conference
16 asked
3 fulfilled
(iii) GMPs contacted by phone
17 asked
6 fulfilled
(iv) GMPs contacted face-to-face
5 asked
4 fulfilled

Respondents
n = 27
n = 3 of these were contacted to confirm or correct suspicious and missing answers

Final number of completed questionnaire replies
n = 27

Figure 1. Flowchart showing questionnaire development, distribution, and responses.
GMP = General Medical Practitioner, RRI = Running-related injury. *Number of GMPs in the North Denmark Region
the purpose of the present study. In pilot study one, an interview was conducted independently with each of four GMPs upon completion of the questionnaire. The interview was aimed at collecting feedback on the level of comprehensibility of the questionnaire instructions and questions, as well as specific suggestions for improvements or modifications of the questions. Pilot study two was performed by two independent GMPs and carried out in a similar manner as the procedure in pilot study one. In each phase, the questionnaire was thoroughly modified according to the feedback, and after pilot study two the final questionnaire was distributed. Details concerning the evaluation and modification upon completion of each pilot study are visualized in Figure 1.

Description of main questions in survey
First, two questions focused on the number of overall consultations in GMP practice caused by both RRIs and non-RRIs: “1) How many consultations do you have per day in an average working week? (State in whole numbers)” and “2) How many consultations have you had in total during the last period of two working weeks? (State in whole numbers)”. Secondly, three questions were targeting consultations caused by RRIs: “3) Have you had at least one consultation concerning a person with a RRI over the past year?”, “4) How many consultations regarding RRIs have you had in total during the last period of two working weeks?” (State in whole numbers)” and “5) How many consultations regarding RRIs have you had per month over the past year? (State in whole numbers)”. The GMPs where informed that all questions should be answered to the best of their assessment. When combining the continuous scale data from the question asking about the GMPs total number of consultations during the last period of two working weeks and the question about the total number of consultations regarding RRIs during the last period of two working weeks, the prevalence proportion of consultations caused by RRIs was estimated using the following equation:

\[
\text{Prevalence proportion} = \frac{\text{Consultations caused by RRIs}}{\text{Total number of consultations in the last two working weeks}} \times 100
\]

The time frame of the prior two working weeks were chosen as the basis for the primary estimate of this study to reduce the risk of subjective recall bias. The question about monthly number of consultations regarding RRIs over the past year was included in order to be able to test the robustness of the primary estimate to this choice of time frame.

The secondary purpose of the study was to estimate the proportion of injured runners referred to additional examinations or treatments. To investigate this, a questionnaire section with the following two questions was designed: “What is the proportion of the RRIs which you refer to secondary examinations and/or treatment?”, with the eligible answers: “0-24%”; “25-49%”; “50-74%”; “75-100%” or “Don’t know”; and “If you refer the patient, to whom do you refer? (select all that apply)”, with the eligible options: “Physiotherapist”; “Chiropractor”; “Orthopaedic surgeon”; “Specialist in sports medicine”; “Acupuncturist” and “Other”.

Data management and statistical analysis:
Data were analysed using Stata/IC version 14.1 (StataCorp, College Station, Texas, USA). Continuous data were evaluated using quartile-quartile plots to evaluate if data were normally distributed, and since they did not follow a normal distribution, we used the median- instead of the mean estimate. Descriptive statistics were used to present the data according to questionnaire categories. In some questions, respondents had the opportunity to include more than one response; therefore the number of responses could exceed 100%.

Trial registration
This was a survey-based study. No trial registration was made.

RESULTS
In total, 27 GMPs completed the questionnaire. Baseline characteristics of the responding GMPs together with the representativeness according to gender,
year. The median proportion of consultations caused by RRIs in the last period of two working weeks was 0.80% [25th percentile = 0.00%; 75th percentile = 1.43%]. The median of the monthly proportion of consultations caused by RRIs was 0.71% [25th percentile = 0.23%; 75th percentile = 1.20%] (Table 2).

A proportion of 25-49% of the consulting injured runners, were referred to additional examination and/or treatment by 48% (n = 13) of the GMPs. None of the GMPs referred 75-100% of the consulting injured runners to additional examination and/or treatment (Figure 2). In case of referral, more

<table>
<thead>
<tr>
<th>Table 1. Representativeness of participating general medical practitioners (GMPs) with regard to gender, seniority, type of practice, number of listed patients per GMP, interest in sports medicine, qualifications in sports medicine, personal interest in running</th>
<th>Participating GMPs % (n=27)</th>
<th>All GMP in one Region in DK % (n=871)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>59.3% (16)</td>
<td>61.1% (532)</td>
<td>0.84</td>
</tr>
<tr>
<td>Female</td>
<td>40.7% (11)</td>
<td>38.9% (339)</td>
<td></td>
</tr>
<tr>
<td><strong>Number of years in practice</strong>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5</td>
<td>34.6% (9)</td>
<td>24.1% (210)</td>
<td></td>
</tr>
<tr>
<td>5-10</td>
<td>7.7% (2)</td>
<td>18.4% (160)</td>
<td>0.36</td>
</tr>
<tr>
<td>10-20</td>
<td>26.9% (7)</td>
<td>32.0% (279)</td>
<td></td>
</tr>
<tr>
<td>&gt;20</td>
<td>30.8% (8)</td>
<td>25.9% (222)</td>
<td></td>
</tr>
<tr>
<td><strong>Type of practice</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-handed</td>
<td>18.5% (5)</td>
<td>24.7% (215)</td>
<td>0.46</td>
</tr>
<tr>
<td>Group</td>
<td>81.5% (22)</td>
<td>75.3% (656)</td>
<td></td>
</tr>
<tr>
<td><strong>Number of list patients per GMP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1000</td>
<td>0.0% (0)</td>
<td>8.0% (70)</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>1000-1499</td>
<td>19.2% (5)</td>
<td>50.9% (443)</td>
<td></td>
</tr>
<tr>
<td>1500-1999</td>
<td>53.8% (14)</td>
<td>36.2% (315)</td>
<td></td>
</tr>
<tr>
<td>&gt;1999</td>
<td>26.9% (7)</td>
<td>4.9% (43)</td>
<td></td>
</tr>
<tr>
<td><strong>Interest in sports medicine</strong></td>
<td></td>
<td></td>
<td>na</td>
</tr>
<tr>
<td>&quot;Yes&quot;</td>
<td>63% (17)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;No&quot;</td>
<td>30% (8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Don’t know&quot;</td>
<td>7% (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Qualifications in sports medicine</strong></td>
<td></td>
<td></td>
<td>na</td>
</tr>
<tr>
<td>&quot;Yes&quot;</td>
<td>37.1% (10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;No&quot;</td>
<td>62.9% (17)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Runner</strong></td>
<td></td>
<td></td>
<td>na</td>
</tr>
<tr>
<td>&quot;No, never&quot;</td>
<td>0.0% (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;No, but I used to&quot;</td>
<td>11.1% (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Yes, once a week&quot;</td>
<td>14.8% (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Yes, twice a week&quot;</td>
<td>7.4% (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Yes, several times a week&quot;</td>
<td>66.7% (18)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n = number of GMPs
na = not available
* One GMP did not provide an answer to this question
** "Do you have a particular interest in sports medicine?"
*** "Do you have specific qualifications in diagnostics and treatments of running-related injuries (courses, scientific experience, ultrasound, other)?"
Central Denmark Region revealed no differences in gender, seniority and type of practice. It is impossible to compare these results with existing data, since no other study has investigated the proportion of consultations because of RRIs in GMP practices. In addition, comparison to data in registries is impossible since RRIs are not registered specifically in the ICPC-2 coding system in Denmark.

The secondary purpose of the study was to investigate the proportion of injured runners, whom the GMP chose to refer to additional examination and/or treatment. Nearly 40% of the GMPs referred between 25% and 49% of the injured runners to physiotherapists, orthopaedic surgeons and specialists in sports medicine. Again, this estimate might be overestimated because of selection bias. In addition, it is unknown how many runners that used the referral for further diagnostics and/or treatment.

In comparison, Moth et al.\(^9\) reported that 6.6% of patients consulting a GMP with a sports-related injury were referred to the hospital.

The present study reveals an impact of running injuries in primary care and that the GMPs recommended injured runners to seek physiotherapy in more than 90% of the cases where the GMP made a referral. According to Figure 2, many of these injured runners are not referred to additional examination and/or treatment. Reasons for this could be many and were not addressed by the survey. The authors suggest that it may be that the GMPs do not believe there is a need for a referral since the runners should be able to handle their injury on their own. Secondly, the GMPs may recommend the runners to seek treatment but refrains from providing a referral, since the cost for the treatment is then partly covered by the health-care system. Finally, it may be that the GMPs are unaware of the pos-

### Table 2. Proportion of consultations in general medical practice caused by running-related injuries

<table>
<thead>
<tr>
<th></th>
<th>Median (%)</th>
<th>25(^{th}) percentile (%)</th>
<th>75(^{th}) percentile (%)</th>
<th>Min (%)</th>
<th>Max (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of 2 weeks</td>
<td>0.80 %</td>
<td>0.00 %</td>
<td>1.43 %</td>
<td>0.00 %</td>
<td>2.50 %</td>
</tr>
<tr>
<td>Monthly</td>
<td>0.71 %</td>
<td>0.23 %</td>
<td>1.20 %</td>
<td>0.00 %</td>
<td>2.00 %</td>
</tr>
</tbody>
</table>

Period of 2 weeks = the last period of two working weeks
Monthly = per month over the past year

**DISCUSSION**

The present study revealed a median proportion of consultations in the prior period of two working weeks and a median monthly proportion of consultations caused by RRIs of 0.80% and 0.71%, respectively. If these proportions of consultations amongst the 27 GMPs submitting questionnaires is generalizable to all 3,495 GMPs in Denmark, RRIs have a considerable impact on the primary health-care system. However, these results should be interpreted with caution, since the estimates reported in the present study might be overestimated owing to selection bias. GMPs interested in the running injury thematic and those who diagnose runners on a regular basis may have been more willing to respond to the questionnaire than those unfamiliar with running. However, this remains speculative and the comparison of the included GMPs and the average GMP in

![Figure 2. Distribution of general medical practitioners (GMPs) with regard to the proportion of running-related injuries, which they refer to additional examination and/or treatment. Y-axis denotes the number of GMPs selecting the category.](image-url)
sibilities for additional examination and treatment options for injured runners in the local community. Assuming the latter case is true, stronger dialogue between physiotherapists working with running-related injuries and GMPs in their local community is indicated. In a survey amongst competitive distance runners, 70% of the runners felt the advice and/or treatment from a physiotherapist was valuable in resolving injury. Although this was better than other health-care professionals that were listed in the survey, there is room for improvement. Referral of the injured runner to a physiotherapist with expertise in running-related injuries may be one important step.

Strength and limitations
The most important strength of the present study was the sampling of data directly from the population of GMPs in Denmark. Little is known about the impact of RRIs on GMP practices, and most other studies concerning the topic are based on data collected from the population of injured runners. In addition, the responding sample of GMPs was representative according to gender, seniority and type of practice when compared to the general population of GMPs in the Central Denmark Region.

However, the present study had some limitations. First, the number of responses (n=27) was low, which, given that more than 370 GMPs were provided with the possibility to respond the electronic questionnaire, leading to a response proportion lower than 7.3%. The response proportion might have been higher if the GMPs had received a compensation for the time-consuming task (approximately 2-3 minutes) of filling out the electronic questionnaire. Second, the majority (66.7%) of the responding GMPs practiced running several times a week, thus presumably having a greater interest in running than the non-responding GMP. This could possibly induce a selection bias (overestimation of the prevalence proportion), since GMPs with a greater interest in running might have a higher number of patients consulting them because of a running-related injury.

Further studies – Ideas for data collection
In future studies, the authors suggest to the provision of minimal compensation to the GMPs responding to the questionnaire in order to improve the response proportion. In addition, to overcome the challenges of one-year recall period, which is difficult to respond to without recall problems, or two-week snapshot, which is affected by seasonal variation, future prospective studies are needed. The present ICPC-2 coding system does not register the causative factors of musculoskeletal problems, and therefore prospective data would have to be collected separately, by for instance using a logbook method, which would enable the GMP in registering precisely each time a consultation is caused by a RRI.

CONCLUSION
The median prevalence proportion of consultations caused by running-related injuries in the past two weeks was 0.80% [25th percentile = 0.00%; 75th percentile = 1.43%]. A proportion of 25-49% of the consulting injured runners, were referred to additional examination and/or treatment by 48% (n = 13) of the GMPs. The low response-proportion highlights the challenges recruiting GMPs willing to respond to questionnaires on running-related injuries. Therefore, these results should be interpreted with caution since the estimates reported in the present study might have been overestimated due to selection bias. If the prevalence proportion of consultations caused by running injuries is generalizable to all 3,495 GMPs in Denmark, the results from the present study suggest that injured runners seek advice in the primary health-care system in Denmark. As a consequence, physical therapists willing to treat runners with running-related injuries may inform the GMPs in their local community about treatment possibilities.

REFERENCES


**ABSTRACT**

**Background:** Costochondritis is commonly encountered in primary care, but is not routinely referred to PT. Costochondritis can last from several weeks to several months, limiting the patient's ability to perform tasks at work and home.

**Purpose:** Identify common impairments and examine the effects of treatment in subjects with costochondritis.

**Study Design:** Retrospective case series

**Case Description:** Eight subjects were referred to physical therapy for costochondritis (mean duration of condition 6.3 ± 1.3 months) and reported that their condition restricted their ability to participate in occupational and fitness activities. The numerical pain rating scale (NPRS) and patient-specific functional scale (PSFS) were administered at the initial evaluation and at discharge. The Global Rating of Change (GROC) scale was only administered at discharge. All subjects received treatment directed at the cervicothoracic spine and ribcage and consisting of manual therapy and exercise.

**Outcomes:** Subjects were seen 4.8 ± 0.9 (mean ± standard deviation) times. All subjects showed clinically meaningful changes at discharge. The mean NPRS decreased by 5.1 ± 1.7 points; the mean PSFS increased by 5.3 ± 1.4 points; and the mean GROC was 5.9 ± 1.1 points. All subjects were able to return to participation in previous activities without restrictions at discharge.

**Discussion - Conclusion:** The results of this case series suggests that PT utilizing an impairment based examination and treatment approach including manual therapy and therapeutic exercise may facilitate the resolution of costochondritis.

**Level of Evidence:** Level IV

**Key words:** Breathing, chest, manual therapy, ribs, thoracic

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2 Tactical Sports OMPT Fellowship, United States Airforce Academy, Colorado Springs, CO, USA

The University of Jamestown Institutional Review Board approved this study and informed consent was obtained from the subjects prior to the collection of data. The authors certify that they have no affiliations or financial involvement with any organization or entity with a direct financial interest in the subject matter or materials discussed in the article.

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INTRODUCTION

Subjects with costochondritis are commonly encountered in primary care, but are not routinely referred to physical therapy (PT). Whereas there is some speculation, the actual etiology of this condition remains unknown. Pain is most commonly localized unilaterally to the second through fifth costochondral junctions, with more than one junction generally affected. Typically, local swelling is not noted in costochondritis, unlike Tietze syndrome. Whereas this condition is considered self-limiting and normally resolves within one year, it can last from several weeks to several months or be recurring, limiting the patient's ability to function in occupational demands and activities of daily living. Pain is often associated with repetitive activities involving the upper extremities or deep breathing, including exertional activities, such as lifting heavy objects or cardiovascular exercise. When subjects are referred to PT, their condition has often progressed to a chronic stage with additional impairments, such as reduced endurance and difficulty performing moderate to heavy manual labor duties, have arisen secondary to compensation for costochondritis. Compounding this difficulty is the current lack of evidence/consensus as to the most effective way to manage this condition.

Current recommendations for medical treatment are analgesics and nonsteroidal anti-inflammatory drugs, heat/ice, and possibly anesthetic/steroid injections. The infrequent referral of subjects with costochondritis to rehabilitation has made it difficult for research to be performed regarding the effects of manual therapy or exercise. At this time only a single research trial exists that supports stretching as an intervention using the visual analog scale for an outcome. All other publications regarding manual therapy and/or exercise specifically for costochondritis have been case reports or case series of no more than two subjects.

Whereas the results of the stretching study are promising, it was a limited retrospective study with a large number of confounding variables that may have affected the results. The remaining case reports used an impairment-based approach, which included manual therapy and exercise directed at the upper thoracic vertebrae, rib cage, and surrounding soft tissues, with significant improvement noted in two or more of the following patient outcomes, the Numeric Pain Rating Scale (NPRS), Visual Analog Scale, Dallas Pain Questionnaire, Functional Rating Scale, Patient-Specific Functional Scale (PSFS), and return to previous performance/activity level.

Given the limited research and lack of a clear consensus regarding optimal treatment strategies, a retrospective review of a series of subjects utilizing an impairment-based approach may provide further insight. It may also provide a better indication of where more formal investigation and research should be directed. The purpose of this case series is to identify common impairments and examine the effect of treatment in subjects with costochondritis.

CASE DESCRIPTIONS

The University of Jamestown Institutional Review Board approved this study and informed consent was obtained from the subjects prior to the collection of data. Eight subjects with costochondritis were retrospectively reviewed for similarities in their evaluative findings and interventions. The subjects were referred to physical therapy by their primary care physicians over a four-month period after having been screened for non-musculoskeletal causes of their symptoms. All subjects had undergone a full medical evaluation for cardiopulmonary issues, including electrocardiography secondary to their reports of “chest pain”. All subjects were referred to PT secondary to demonstrated inability to perform full military duties and participate in mandatory fitness training, particularly push-ups and running, without exacerbation of symptoms. Subject demographics are shown in Table 1. The majority of cases were due to either physical activity or respiratory infection. In two subjects, there was an insidious onset and additional questioning during the patient interview and examination did not suggest any possible causes. Patient’s primary pain was isolated to the costosternal junctional area on at least two unilateral consecutive costosternal joints of the second through seventh ribs. The common primary aggravating factors reported by the subjects were any activity that caused heavy breathing and/or end-range horizontal abduction and adduction of the shoulder.
INITIAL EVALUATION
All subjects were screened and evaluated using a standardized PT examination for cervicothoracic conditions. All examination, evaluation and treatment was conducted by a single physical therapist with six years of clinical experience, board certified as an orthopedic clinical specialist, and fellowship trained in orthopedic manual physical therapy.

Outcomes Instruments
None of the subjects reported any radicular or referred symptoms. The subjects reported an average of the best, worst and current rating in the prior 24 hours on NPRS of 5.6 (range, 4–8) with specific activities noted to increase pain by an average of 2.0 points. The NPRS has been demonstrated to be valid in chronic musculoskeletal pain conditions with a change of 1.0 point, or 15%, identified as the minimal clinically important difference (MCID) and excellent (r=0.79–0.92) test-retest reliability when administered at least two times during the week.21,22 The NPRS was completed by all subjects at each visit to monitor condition.

The PSFS was administered to all eight subjects with an average score of 4.5 (range, 3–6). The PSFS has been demonstrated to be valid in neck pain and cervical radiculopathic conditions, with a change of 2.0–2.2 points as the MCID and excellent (r=0.82–0.92) test-retest reliability. The PSFS was completed per standard operating procedures at initial evaluation and discharge. Two common patient specific functions noted with all subjects were to be able to perform all duties without restriction and to be able to participate in fitness training without restriction.

The Global Rating of Change (GROC) was administered to all eight subjects at the last appointment prior to the cessation of the episode of care. The GROC has been demonstrated to be valid in cervical and upper extremity conditions. A score between ±1 and ±3 indicates a small change; a score between ±4 and ±5 indicates a moderate change; and a score between ±6 and ±7 indicates a large change.26

If treatment duration had lasted longer than four weeks a formal re-evaluation and completion of the PSFS and GROC would have been completed at that time per clinic standard operating procedures.

Observations/Palpations
All subjects positioned themselves with varying degrees of a forward head, shoulder protraction, and increased upper (T3–5) and middle (T5–10) thoracic kyphosis. Additionally, all subjects performed splinting of upper torso by the upper extremities when seated for symptomatic relief if an elevated surface such as chair arms or a table was available. Palpation with anterior to posterior pressure up to
the point of initiation of rib movement at the costosternal joints reproduced the subjects’ symptoms and demonstrated tenderness of at least two consecutive costosternal junctions from the second to the sixth ribs unilaterally, with pain present on the patient’s dominant side in six of the eight cases. All subjects reported reproduction of pain with deep inhalation and six of eight-reported pain with normal exhalation (Table 2).

Palpation with pressure to the point of fingernail blanching applied to the pectoralis major/minor, latissimus dorsi, upper trapezius, and scalene muscles did not reproduce subjects’ symptoms. No active trigger points were identified corresponding to the subjects’ pain patterns and symptoms; however, it is noteworthy that the pectoralis minor is deep to the pectoralis major, making it difficult to detect trigger points if they are present.30

### Range of Motion

Active range of motion was tested for cervical spine, thoracic spine, ribcage, and shoulders bilaterally as described by Flynn et al.19 Cervical active range of motion was reported to be associated with “stiffness” or “discomfort” at end-range cervical flexion and rotation to the noninvolved side in 50% of subjects. All subjects reported symptom reproduction with overpressure applied with rotation to the noninvolved side. Thoracic extension was observed to be limited both actively and passively in all subjects with symptom reproduction and “stiffness” or “discomfort” at end-range. Excursion of ipsilateral upper and middle ribs was diminished during the subjects’ respiratory cycle. Ipsilateral horizontal shoulder adduction past 10 degrees reproduced symptoms intermittently in all subjects.

### Accessory Motions

Unilateral posterior anterior glides of the cervicothoracic junction (C7–T1)27,28 and upper thoracic (T1–7) spine29 were hypomobile and reproduced symptoms in all subjects when tested ipsilateral to corresponding symptomatic costosternal joints. The first and/or second ribs were hypomobile in six subjects, with partial replication of subjects’ symptoms. Hypomobility in the costovertebral joint of ribs 3–7 was present in only four subjects; however, symptom reproduction, including pain, occurred in all subjects when the symptomatic costosternal joint area was assessed29 (Table 2).

### Muscle Length

All subjects were assessed for length of pectoralis major/minor, latissimus dorsi, upper trapezius, and scalene muscles.27,28 All eight subjects were found to have increased tightness and/or guarding in the pectoralis major/minor and upper trapezius muscles, with greater tone on the involved side. Six subjects had increased tone/tightness in the scalene muscles of the involved side and 50% of the subjects demonstrated increased tightness in the latissimus dorsi on the involved side (Table 3).

### Special Tests

The Upper Limb Tension Test A (ULTT),27,28,31 Spurling’s Test,27,28,31,32 and the Cervical Distraction Test27,28,31,33 were performed to rule out any cervical referral and were negative for all subjects, with a negative ULTT decreasing the possibility of the

### Table 2. Palpation of Costosternal Joints and Symptom Provocation with Movement

<table>
<thead>
<tr>
<th>Patient</th>
<th>Palpation Rib Tenderness</th>
<th>Thoracic Extension</th>
<th>Deep Inhalation</th>
<th>Full Exhalation</th>
<th>CPA C7–T7</th>
<th>Costotransverse PA 1–7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rt R2–4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C7–T4</td>
<td>Rt 1–2</td>
</tr>
<tr>
<td>2</td>
<td>Lt R3–6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C7–T6</td>
<td>Lt 1–2</td>
</tr>
<tr>
<td>3</td>
<td>Rt R3–4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C7–T4</td>
<td>Lt 1–2</td>
</tr>
<tr>
<td>4</td>
<td>Lt R4–5</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>T3–5</td>
<td>Lt 3–5</td>
</tr>
<tr>
<td>5</td>
<td>Rt R2–4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C7–T4</td>
<td>Rt 1–2</td>
</tr>
<tr>
<td>6</td>
<td>Rt R4–5</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>T3–6</td>
<td>Rt 4–5</td>
</tr>
<tr>
<td>7</td>
<td>Rt R3–4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C7–T4</td>
<td>Rt 1–2</td>
</tr>
<tr>
<td>8</td>
<td>Rt R3–6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C7–T6</td>
<td>Rt 2–7</td>
</tr>
</tbody>
</table>

Mean 100.0% 100.0% 75.0%

SD 0.0% 0.0% 46.3%

patient's condition being related to cervical radiculopathy to less than 10%. The Cervical Rotation Lateral Flexion (CRLF) Test was performed, and six subjects demonstrated restriction in motion and an early firm end feel, with symptom reproduction in four of the six subjects, indicating a possible dysfunction that was contributing to the patient's condition at the first/second rib.\textsuperscript{34-36} (Table 3)

As costochondritis is normally a diagnosis of exclusion, no special tests have been identified as valid for differential diagnosis. Palpation of the involved costochondral segments with symptom reproduction is the only recommended physical examination technique cited at this time.\textsuperscript{3}

### INTERVENTION

Intervention was an impairment-based model addressing the individual findings for each patient, prioritized according to the approach of treating thoracic spine prior to ribcage.\textsuperscript{37} Each manual–therapy-based intervention was matched with an appropriate home exercise to improve carry-over (Table 4). All subjects were seen one to two times per week, determined by the subjects' availability and duties, and treated four to six times (average 4.8) over a three to four week period.

The cervicothoracic junction and upper thoracic vertebral region were treated first with a seated manipulation directed toward the identified region of dysfunction. Up to three attempts were made, rechecking of thoracic gross and accessory movement after each attempt, if successful PT progressed to next prioritized area of impairment. All subjects were instructed in performance of a home exercise consisting of thoracic/rib cage self-mobilization for extension and flexion timed with breathing (Figure 1).

First and second rib restrictions were treated with seated mobilization/manipulation and affected subjects were instructed on self-mobilization with a belt for their home exercise. First/second rib dysfunction received grade 3 to 4 mobilizations for up to three sets of 30 seconds each, unless an appropriate end feel was noted, at which time the technique progressed to a high-velocity low-amplitude manipulation for the appropriate area with a maximum of two attempts. The CRLF was used as asterisk sign and rechecked between sets of mobilizations or attempts at manipulation. The self-mobilization exercise previously instructed for thoracic dysfunctions also provides a self-mobilization for first/second rib dysfunctions, so no specific exercise was matched with this manual intervention (Table 4).

Hypomobile third to seventh ribs were treated with Grade 3 to 4 posterior to anterior mobilization techniques directed toward the costotransverse and/or anterior to posterior mobilization techniques directed toward the costosternal joints for up to three sets of 30 seconds each. Rib mobility was assessed prior to mobilization and reassessed after each set. Subjects were then instructed on an upper thoracic/rib cage extension/flexion/rotation self-mobilization exercise timed with breathing for their home exercise (Figure 2).

Tight muscles, including the pectoralis major/minor, latissimus dorsi, upper trapezius, and scalenes, were treated according to their assessment findings. Contract/relax soft–tissue-release tech-

<table>
<thead>
<tr>
<th>Patient</th>
<th>Pectoralis Major Tightness</th>
<th>Pectoralis Minor Tightness</th>
<th>Latissimus Dorsi Tightness</th>
<th>Upper Trapezius Tightness</th>
<th>Levator Scapulae Tightness</th>
<th>Scalenae Tightness</th>
<th>CRLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Left</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Mean</td>
<td>100.0%</td>
<td>100.0%</td>
<td>50.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>62.5%</td>
<td>75.0%</td>
</tr>
<tr>
<td>SD</td>
<td>0.0%</td>
<td>0.0%</td>
<td>53.5%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>51.8%</td>
<td>46.3%</td>
</tr>
</tbody>
</table>

SD, standard deviation. CRLF, cervical rotation lateral flexion
Figure 1. Thoracic flexion/extension self-mobilization timed with breathing. (A) Patient begins exercise in thoracic flexion sitting on low-back chair with hands interlocked behind cervicothoracic junction and elbows pointing toward ipsilateral knees with full exhale. (B) Patient then performs thoracic extension over back of chair in conjunction with horizon abduction of elbows and full inhalation timed with movement. Return to starting position.

Table 4. Impairment-Based Findings, Prevalence, and Interventions

<table>
<thead>
<tr>
<th>Impairment Finding</th>
<th>Prevalence</th>
<th>Intervened</th>
<th>Manual Therapy</th>
<th>Therapeutic Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypomobile C7–T1</td>
<td>8/8</td>
<td>8/8</td>
<td>Seated distraction cervicothoracic junction mobilization/manipulation</td>
<td>Thoracic flexion/extension self-mobilization timed with breathing (Figure 1)</td>
</tr>
<tr>
<td>Hypomobile T2–7</td>
<td>8/8</td>
<td>8/8</td>
<td>Seated distraction upper/mid thoracic mobilization/manipulation</td>
<td>Thoracic flexion/extension self-mobilization timed with breathing (Figure 1)</td>
</tr>
<tr>
<td>Tight pectoralis major/minor</td>
<td>8/8</td>
<td>8/8</td>
<td>Contract-relax soft-tissue release for pectoralis major/minor</td>
<td>Corner stretch for pectoralis major/minor</td>
</tr>
<tr>
<td>Tight upper trapezius</td>
<td>8/8</td>
<td>8/8</td>
<td>Contract-relax soft-tissue release for upper trapezius</td>
<td>Self-mobilization/stretch with belt/towel for first/second rib, anterior/middle/posterior scalenes and upper trapezius</td>
</tr>
<tr>
<td>Hypomobile rib 1/2</td>
<td>6/8</td>
<td>4/8</td>
<td>Seated first/second rib mobilization/manipulation</td>
<td>Self-mobilization/stretch with belt/towel for first/second rib, anterior/middle/posterior scalenes and upper trapezius</td>
</tr>
<tr>
<td>Tight anterior/middle/posterior scalene</td>
<td>6/8</td>
<td>4/8</td>
<td>Contract-relax soft-tissue release for anterior/middle/posterior scalenes</td>
<td>Self-mobilization/stretch with belt/towel for first/second rib, anterior/middle/posterior scalenes and upper trapezius</td>
</tr>
<tr>
<td>Hypomobile rib 3–7</td>
<td>4/8</td>
<td>2/8</td>
<td>Supine costovertebral joint manipulation</td>
<td>Thoracic flexion/extension with unilateral rotation self-mobilization timed with breathing (Figure 2)</td>
</tr>
<tr>
<td>Tight latissimus dorsi</td>
<td>3/8</td>
<td>1/8</td>
<td>Contract-relax soft-tissue release for latissimus dorsi</td>
<td>Kneeling prayer stretch with bench for latissimus dorsi</td>
</tr>
</tbody>
</table>
of care based on response to the previous treatment interventions. Manual therapy for specific impairments was discontinued if impairment was no longer present, whereas the specific exercises for the impairment were continued three times per day at home and/or in clinic for a minimum of two weeks after manual therapy intervention for specific impairment was discontinued, to reinforce and maintain the improvements in the patient’s condition (Table 4).

Subjects were reassessed at each visit for all previous positive findings to modify each patient’s plan

Techniques were directed at the pectoralis major/minor, anterior/middle/posterior scalene, and/or latissimus dorsi muscles for up to three sets of 30 seconds each, with approximately 25% resistance applied by the patient. Subjects were then instructed in the corresponding self-stretch for their home exercise programs for the affected muscles (Table 4).

Subjects were reassessed at each visit for all previous positive findings to modify each patient’s plan

Table 5. Number of Times Intervention was Applied to Patient

<table>
<thead>
<tr>
<th>Patient</th>
<th>Cervicothoracic Junction</th>
<th>Upper Thoracic</th>
<th>Pectoralis Major/Minor</th>
<th>Upper Trapezius</th>
<th>Rib 1/2</th>
<th>Ant/Mid/Post Scalene</th>
<th>Rib 3–7</th>
<th>Latissimus Dorsi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>4</td>
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<tr>
<td>6</td>
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<td>3</td>
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<td>3</td>
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<tr>
<td>7</td>
<td>2</td>
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<tr>
<td>8</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Ant, anterior; Mid, middle; Post, posterior.
OUTCOMES
All patient outcome measures indicated clinically meaningful improvements in an average of 4.8 total sessions including the initial evaluation (Table 6). All subjects were able to resume normal duties and military fitness training without symptoms, including running and push-ups, after a standardized 45-day reconditioning phase for fitness training (as directed by USAF instructions), initiated after discharge from physical therapy.

DISCUSSION
This case series provides preliminary evidence that an impairment-based approach addressing motion impairments at the cervicothoracic spine may be beneficial to subjects with costochondritis. All subjects reported the typical signs and symptoms of costochondritis, including tenderness at the costosternal junction of the second to fifth ribs unilaterally, with symptom exacerbation secondary to exertion, and/or horizontal abduction/adduction.

An impairment-based approach was effective with the subjects in this case series, but it remains to be seen if there is a more effective approach to treatment secondary to the limitations presented by a case series, including lack of comparison and control groups. It has been shown that the biomechanics of the thoracic vertebrae and rib cage are interdependent.38,39 This interdependence, combined with the patient presentations, provides face validity to the interventions directed to these regions. Seated thoracic manipulation was chosen due to the effectiveness, efficacy, and safety of these techniques.40-42 Manual therapy techniques were selected based on the authors’ experience because they are specific to the identified impairment, easy to perform, safe, and well tolerated by most subjects.43 Manual therapy techniques also allow the clinician to carry on a running dialogue with the patient during treatment, thus permitting a continuous assessment of symptoms and a corresponding modification of amplitude and/or cadence. A maximum of three attempts at manipulation were chosen based on previously published pragmatic studies.40-42

Four subjects required interventions directed only at the cervicothoracic junction and upper thoracic vertebrae for resolution of their impairments and condition, and there was no need to address the first to seventh ribs. Six of the subjects also had hypomobility and symptom reproduction noted in the first and second ribs, which was addressed with interventions in four subjects when not resolved by intervention at the cervicothoracic junction and upper thoracic vertebrae. This can be explained by the biomechanical interdependence of the ribs and vertebrae in the upper thorax.38,39

Home programs were prescribed based on their ability to address one or more impairments, while being simple to perform and requiring minimal equipment. This ensured that no more than five exercises were prescribed for any of the home exercise programs, in order to improve patient compliance.44,45

It is unclear as to why there was a delay in referral to physical therapy for these subjects of an average duration of 6.3 months. It could be hypothesized, that given the high number cases seen in primary care that clear naturally, that the referring physi-

<table>
<thead>
<tr>
<th>Patient</th>
<th>Visits (N)</th>
<th>NPRS (Pre)</th>
<th>NPRS (Post)</th>
<th>NPRS Change</th>
<th>PSFS (Pre)</th>
<th>PSFS (Post)</th>
<th>PSFS Change</th>
<th>GRC</th>
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<td>6</td>
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<tr>
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<td>8</td>
<td>4</td>
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<td>+7</td>
</tr>
<tr>
<td>Mean</td>
<td>4.8</td>
<td>5.6</td>
<td>0.5</td>
<td>5.1</td>
<td>4.5</td>
<td>9.8</td>
<td>5.3</td>
<td>+5.9</td>
</tr>
<tr>
<td>SD</td>
<td>0.9</td>
<td>1.4</td>
<td>0.8</td>
<td>1.7</td>
<td>1.2</td>
<td>0.5</td>
<td>1.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

N, number; NPRS, numerical pain rating scale; PSFS, patient-specific functional scale; GRC, global rating of change; SD, standard deviation.
cians believe that physical therapy intervention was unnecessary for this condition. Another possible hypothesis is that with these subjects presenting with "chest pain" a referral was thought to be inappropriate. However, the exact reason for the delayed in referral of the subjects is still unclear at this time.

**Limitations**

As is typical in case reports or case series, the study design does not allow for the determination of cause and effect due to lack of a control group. Some methods used in this study, such as accessory motion assessment and symptom provocation, may be significantly limited in their reliability and diagnostic utility, but may be of assistance in directing an impairment based treatment approach. A properly designed randomized controlled study would provide additional information that may help overcome the significant limitations of this case series. Future research also should attempt to identify the MCID of the NPRS and PSFS for this population as well as determine the most appropriate type and dose of manual therapy and home exercise program.

**CONCLUSION**

The results of this case series suggest that an impairment based approach to examination and treatment of individuals with costochondritis was effective for pain reduction, and patient specific improvements in function. The question remains: "Are the symptoms experienced with costochondritis due to direct injury at the costochondral region or are they the result of compensation for changes in other areas of the axial skeleton? Further research and investigation will be required to answer this question.

**REFERENCES**

17. Ian Rabey M. Costochondritis: Are the symptoms and signs due to neurogenic inflammation. Two cases that responded to manual therapy directed towards posterior spinal structures. Man Ther. 2008;13(1):82-86.
ABSTRACT

Background and purpose: Muscle dysfunction is very common following musculoskeletal injury. There is very little evidence to suggest that muscle function may be positively impacted by soft tissue interventions, such as dry needling. The purpose of this case report is to describe the immediate effect of dry needling on muscle thickness in a subject after shoulder surgery.

Case Description: A 22 year-old competitive gymnast presented seven months post shoulder surgery with significant impairments and functional limitations. Previous physical therapy focused on restoration of range of motion and strength using general exercise interventions, but the subject had persistent tightness and weakness of musculature of the shoulder complex. A subject-specific physical therapy program including manual physical therapy resulted in significant initial improvement, but lack of flexibility and weakness of the rotator cuff limited progress. Dry needling was used to address persistent myofascial trigger points.

Outcomes: Immediately after dry needling the infraspinatus, the muscle's thickness was significantly improved as measured by rehabilitative ultrasound imaging. There was a corresponding increase in force production of external rotation at 90 degrees of abduction.

Discussion: Minimal research exists that validates the potential of dry needling on muscle function, as assessed by muscle thickness measured using rehabilitative ultrasound imaging. The results of this case report suggest that dry needling contributed to improvement in muscle thickness and strength in a subject with muscle dysfunction following an injury.

Level of Evidence: 4

Key words: Dry needling, muscle thickness, trigger points
BACKGROUND AND PURPOSE

Muscle dysfunction is commonly identified among subjects with persistent pain syndromes and musculoskeletal injuries.\(^1,2\) Myofascial trigger points (MTrPs) develop within muscles associated with musculoskeletal pathology and may create a variety of symptoms and impairments including local and referred pain, decreased range of motion, muscle stiffness, and altered muscle function.\(^3-12\) MTrPs are hypothesized to occur as a consequence of muscle overload either from prolonged low-level exertion (occupational posturing), repetitive eccentric and concentric contractions (throwing a ball), or direct traumatic overload (whiplash).\(^13\)

Specifically, muscle inhibition following a musculoskeletal injury is a limiting factor to impairment resolution and functional progression. The exact mechanism of muscle inhibition has not been definitively identified, but appears to be due to deactivation of the muscle by the central nervous system in response to an injury, pain, or both.\(^14\) This response occurs as a protective means to prevent further injury to the damaged structure.\(^14-16\) However, even after the body has repaired the injured tissue, persistent muscle weakness and fatigue results when the muscle inhibition is left unaddressed, and ultimately, the muscle atrophies.\(^16\) The sequela of not treating muscle inhibition may include poor functional outcome and poor subject satisfaction.

A relatively novel mode of measuring muscle function in the clinic is with rehabilitation ultrasound imaging (RUSI). Measurement of the muscle thickness during contraction, relative to its resting thickness, provides an indirect measure of the muscle’s function.\(^17\) Muscle function is implied to be greater if there is an increase in muscle thickness during the contracted state as compared to the resting state. While the clinimetrics of RUSI are still developing, it appears to be a very promising tool for indirect measurement of muscle function in the trunk\(^17\) and shoulder region.\(^18,19\)

Most interventions that target muscle inhibition following a joint injury have focused on influencing the joint’s mechanoreceptors, the peripheral nervous system, or the central nervous system.\(^15\) A comprehensive systematic review\(^15\) of interventions that combat muscle inhibition of the quadriceps revealed that TENS application had the strongest and most consistent benefit for improving muscle contractibility. Manual therapy had weak immediate effects, however, as only one study was identified that directly manipulated the soft tissue.\(^20\) Specifically, the performance of active release technique for subjects with anterior knee pain did not reduce muscle inhibition or increase muscle strength immediately or within 20 minutes after the intervention.\(^20\) Variable findings are reported when considering soft tissue mobilization on a more general measure of muscle function such as force production.\(^8,21-24\) Direct intervention of the MTrP may be required to improve the function of the pathological muscle.

Dry Needling (DN) has become a recognized and accepted form of treatment of MTrPs among many different medical professionals.\(^3,25\) DN has been defined by the American Physical Therapy Association as “a skilled intervention that uses a thin filiform needle to penetrate the skin and stimulate underlying myofascial trigger points, muscular and connective tissues for the management of neuromusculoskeletal pain and movement impairments”.\(^26\) While this intervention has received increasing attention as a modality for treatment of musculoskeletal disorders, quality research is limited with regard to its influence on MTrP symptoms, especially motor function.\(^10\) The purpose of this case report is to describe the immediate effect of dry needling on muscle thickness in a subject after shoulder surgery.

CASE DESCRIPTION: SUBJECT HISTORY AND SYSTEM REVIEW

A 22-year-old female former collegiate gymnast presented to the physical therapy clinic seven months post surgical repair of a posterior labral tear of the right shoulder. She injured her shoulder during gymnastics practice five months prior to the surgery. However, because the competitive season had already started, she elected conservative management and participated in gymnastics with activity modifications. Immediately after the competitive season, the subject had surgery to repair the posterior labrum. She initially participated in physical therapy for six months, and the focus of therapy was self-directed restoration of range of motion (ROM)
and standard strengthening exercises. She was frustrated with her continued limitation in shoulder mobility and strength which disrupted routine daily activities that required her to reach overhead. Therefore, the subject sought treatment at the authors' facility. The subject had no other significant medical conditions.

CLINICAL IMPRESSION #1
After taking a thorough history, the exact cause of the subject's limited range of motion (ROM) and strength could not be specified. Given that the surgical procedure was a posterior Bankart repair without involvement of other static or dynamic structures, there was no suspicion of iatrogenic involvement such as excessive tightening of the capsule or rotator cuff contracture. Also, given that the subject was young and had excellent health without any comorbidities, it seemed unlikely that she had developed any capsular adhesions from pathologies such as metabolic disorders. The authors' experience suggests that patients who have joint instability frequently develop muscle dysfunction in response to extreme muscle guarding of the shoulder musculature as they attempt to improve dynamic stability. Her description of the post-operative rehabilitation program also implied a non-specific exercise regimen that did not address specific limitations of muscle and capsular restrictions, such as inferior capsular restrictions, which limit shoulder elevation.

Examination
Posture: The subject had an endomorphic body type. Her BMI was 19.39 kg/m², and she had good general muscle definition and tone. She had a minimal forward head and anteriorly tilted scapulae, but the right scapula presented with a predominant Type 3 dysfunction as defined by Kibler et al. 27

Cervical Screen: The cervical spine had full ROM without restriction or pain. There was no reproduction of symptoms with assessment.

Range Of Motion (ROM): Examination revealed significant limitations in active (AROM) and passive (PROM) ROM of the left shoulder. The limitations were especially remarkable with shoulder elevation (Table 1) as there was observable scapular elevation as a compensation strategy during AROM, and PROM required manual scapular stabilization. All end ranges of ROM were painful with stiff capsular endfeels.

Joint Mobility: Glenohumeral and scapulothoracic articulations were significantly restricted and stiff in all planes. Joint restrictions varied between Grade 1 and Grade 2 hypomobility.

Strength: Left shoulder complex musculature demonstrated strength deficits per manual muscle testing (Table 1). 28

Palpation: Palpation revealed a generalized decrease in soft tissue mobility in all muscles adjacent to

<table>
<thead>
<tr>
<th>Table 1. Clinical measurements taken at initial evaluation, three weeks, and six weeks after the initial evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoulder ROM</strong></td>
</tr>
<tr>
<td>Flexion</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Abduction</td>
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<td></td>
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<tr>
<td>ER at 0</td>
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<td></td>
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<tr>
<td>ER at 90</td>
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<td>IR at 90</td>
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<td>Strength</td>
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</table>

IE=Initial evaluation; AROM= Active range of Motion; PROM= Passive range of motion; ER= External rotation
the scapulothoracic and glenohumeral articulations. Highly irritable active and latent MTrPs were present throughout the region, specifically in the rotator cuff muscles. The most significant MTrPs were noted in the muscle belly of the infraspinatus. They were identified by point tenderness that replicated the subject's pain and were associated with a taut band within the muscle. Several of the MTrPs responded to palpation with a local twitch as described by Simons, Travell and Simons. 

Neurological: Sensory was intact to light touch throughout the upper extremity. Reflexes and myotomes were unremarkable.

Pain Score: The visual analog scale was used to assess pain with 0 representing no pain and 10 representing the worst pain imaginable. The patient's average Numeric Pain Rating Scale was 3/10 with her current pain = 2/10, worst pain = 5/10, and her least pain = 2/10.

Functional Outcome: The QuickDASH was used to assess the patient's function. There are three sections to the questionnaire: the Disability/Symptom section, the Work section, and the Sports section. Each section is scored 0-100 with 0 representing no disability and 100 representing complete disability. The subject's score on the Disability/Symptom section was 47%, the Work section was 0% and the Sports/Performing Arts module was 100%.

**CLINICAL IMPRESSION #2**

Given the longevity of the post-surgical impairments, one hypothesis was that the surgical procedure had failed and the patient still had joint pathology. However, due to the lack of trauma or reinjury to the shoulder, joint derangement as a cause of ROM and strength limitations was low on the list of differential diagnoses. Neurologically, there were no indications of sensory or reflex deficits. Shoulder complex musculature was diminished in all planes and was associated with shoulder discomfort. Moreover, resistance testing of the distal extremity did not indicate nerve root or peripheral nerve involvement.

Palpation of the shoulder musculature revealed multiple active and latent MTrPs, most notably within the infraspinatus muscle belly, which replicated glenohumeral joint pain that was reported during ROM and resistance testing. ROM was restricted in all planes with stiff with capsular endfeels. (Table 1) The presence of palpation findings with concordant ROM restrictions and strength deficits verified the presence of MTrPs as described by Simons, Travell and Simons. 

Assessment of joint mobility within the midrange of ROM confirmed stiffness of the joint capsule. Specifically, inferior glide, anterior glide and posterior glide demonstrated Grade I hypomobility. Based on the results of the examination, the subject appeared to have generalized soft tissue restrictions in the glenohumeral joint, scapulothoracic articulation and the surrounding musculature as well as extensive MTrP activation which influenced muscle function.

**INTERVENTION #1**

Physical therapy focused on an individualized program to improve shoulder mobility, strength and scapular stabilization. ROM limitations were specifically addressed with various manual therapies including joint mobilization, instrumented soft tissue mobilization, MTrP release, and manual stretching. Within three weeks, there were dramatic improvements in ROM and strength (Table 1).

**CLINICAL IMPRESSION #3**

After the initial gains from the individualized program, impairment and functional progress plateaued. Although ROM improved immediately following a treatment, the subject continued to complain of weakness at the endranges of motion and consequently, the stiffness and immobility returned quickly after each session. Given the perpetuation of highly irritable trigger points in the scapulohumeral muscles, DN was incorporated into her treatment plan for a more direct, targeted, and time-efficient intervention for the MTrPs. Due to the complexity of dysfunction in the shoulder complex muscles, the infraspinatus was chosen to evaluate the influence of DN on muscle thickness given its influence on shoulder stability and function.

**INTERVENTION #2**

A physical therapist certified in dry needling performed the additional interventions. In the state of Virginia a dry needling certified physical therapist must have completed at least 54 hours of post pro-
ders using rehabilitative ultrasound imaging (RUSI). The RUSI device used to take images was the Interson SR 7.5 MHz (Interson Corporation, Pleasanton, California) with a linear array transducer. Images were taken at the superior-medial margin of the infraspinatus and the inferior aspect of the infraspinatus. Because the subject had prominent latent MTrPs in the inferior aspect of the infraspinatus, which was to be a focus of DN, we chose to also measure the thickness of this part of the muscle. The superior border of the RUSI soundhead was placed 5 cm distal from the intersection of the spine of the scapula and the medial border of the scapula. The medial border of the soundhead was parallel and immediately adjacent to the medial border of the scapula. A marker was used to outline the sound head on the patient’s skin to improve the accuracy of measuring the same area of the muscle when subsequent measurements were performed. Three images were taken of each shoulder at rest and at a 50% MVIC of external rotation, as measured by a HHD. On the right shoulder, 50% MVIC images were also taken after the DN.

OUTCOMES
Immediately prior to DN, the thickness of the right inferior infraspinatus was at an approximate 20% deficit compared to the left with a consequent strength deficit of 35% as measured with HHD. There was no difference in muscle thickness of the superior infraspinatus between the left and right shoulders. Immediately following the DN, external rotation strength increased by approximately 30%, and the RUSI measurement of the inferior infraspinatus thickness increased by 25%. (Figure 1) This
Given the effect of latent MTrPs on activation patterns, Lucas et al. assessed the effects of DN and passive stretching of the latent MTrPs on activation patterns during scaption. Following the treatment, the activation of the infraspinatus and the upper trapezius significantly changed to resemble the timing of the control group. The timing of activation also became more consistent for all of the shoulder complex muscles. The authors suggest that the MTrPs are part of a neurological loop that when successfully diminished allow for normalization of muscle function as assessed by activation patterns and thus proficiency of movement.

Koppenhaver et al. evaluated the effect of DN on infraspinatus function among subjects diagnosed with subacromial pain syndrome. No significant changes in muscle function were identified immediately after DN to three general locations of common MTrPs. Similar to the current report, the authors measured the thickness of the infraspinatus by RUSI, but only the superior-medial aspect of the infraspinatus was measured. Their findings confirm that DN of the inferior aspect of the muscle did not result in a change of thickness in the superior-medial infraspinatus. As Koppenhaver et al. stated, this may have been an important limitation of their study because the measurement occurred at a section of the muscle that was distant from the treatment site. Although the boundaries of the sound head were marked over the inferior infraspinatus in the current study in an attempt to accurately relocate its position before and after DN, definitive anatomical boundaries must be identified to provide reliable RUSI measurements of this region between subjects and treatment dates.

With regard to the subject, the portion of the infraspinatus adjacent to the focal region of DN demonstrated a large increase in thickness equal to

<table>
<thead>
<tr>
<th>Table 2. Infraspinatus thickness (mm) at rest and at 50% MVIC before and after dry needling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Inferior Infraspinatus</td>
</tr>
<tr>
<td>Left Inferior Infraspinatus</td>
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<tr>
<td>Right Superior Infraspinatus</td>
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<td>Left Superior Infraspinatus</td>
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</table>
CONCLUSION

The results of this case report highlight the potential benefit of DN on muscle function as measured by RUSI (muscle thickness) and force production (hand-held dynamometry). After a prolonged period of nonspecific rehabilitation, the subject demonstrated significant muscle dysfunction associated with MTrPs. DN of the MTrPs in the infraspinatus resulted in an immediate increase in muscle thickness and a concurrent increase in strength. Healthcare practitioners should consider DN as an adjunctive intervention to promote improvements in muscle function when muscle dysfunction is present.

REFERENCES


ABSTRACT

A 64-year-old male fell from an altitude of 10 m while paragliding after stalling due to the wind. The purpose of this case report is to describe the outcomes after multiple injuries sustained during a paragliding accident, including a potentially life-threatening injury to the thoracic aorta. The subject sustained a bite wound on his tongue, injuries to his chest (left side) and back, and a right forearm deformity. Enhanced whole body computed tomography (CT) revealed fractures of the bilateral laminae of the second and third cervical bones, right first rib, the tenth thoracic vertebral body (compression type), second lumbar vertebral body (burst type) and the right radius. Other injuries included an injury to the thoracic aortic arch and the presence of intraabdominal fluid collection without perforation of the digestive tract. Endovascular treatment was selected for the aortic injury because of multiple injuries. Immediate management included hypotensive rate control therapy using calcium and a beta blocker. On the fourth hospital day, the subject underwent deployment of a stent-graft to the aorta and subsequent surgical immobilization for the lumbar burst fracture. He also underwent surgical immobilization of the radial fracture and was discharged on the 28th hospital day. First responders or physicians should consider the possibility of aortic injury when treating patients who suffer falls while paragliding and provide appropriate management. Failure to provide appropriate management of an aortic injury could result in death.

Level of Evidence: 4

Key words: Aortic injury; multiple fractures; paragliding
INTRODUCTION
Paragliding is an increasingly popular hobby, as people try to find new and more adventurous activities.¹ There are many recreational and competitive paragliding events held throughout the world. However, there is also substantial and inherent danger with this sport. For this reason, as well as the inexperience of many operators, injuries occur frequently.¹ The role of the sports physical therapist (PT) is typically as a part of the sports medicine team, often being present during performance of recreational sports. The PT can assume the role of an emergency medical responder (EMR) whose primary role is the management of individuals in emergency type situations.² In this role, the PT must be prepared to handle any type of emergency situation, which may occur related to medical conditions and/or acute orthopedic/sports injuries.²

Injuries sustained while paragliding tend to occur at the spine, pelvis and lower extremities.³⁵ Lautenschlager et al analyzed 86 injuries associated with paragliding in a prospective study and found that 60% of all accidents happened during the landing phase, 26% at launching and 14% while in-flight.³ The purpose of this case report is to describe the outcomes after multiple injuries sustained during a paragliding accident, including a potentially life-threatening injury to the thoracic aorta.

CASE PRESENTATION
The subject of this case report is a 64-year-old male fell who from an altitude of 10 m while paragliding, after stalling due to the wind. A physician-staffed helicopter was called to transport the subject after his accident. On arrival at the hospital, the subject was conscious with a blood pressure of 140/98 mmHg, heart rate of 78 beats per minute, SpO₂ of 100% under 10 L/minute of oxygen delivered via a reservoir mask, and a body temperature of 36.5°C. He had a bite wound on his tongue, displayed tenderness to palpation of the left side of the chest and the back, as well as a right forearm deformity.

Sonographic assessment for trauma showed fluid collection in his mesentric interval. A biochemical analysis of the blood revealed leukocytosis (12,600/µL) and increased creatinine phosphokinase level (401 IU/L) and D-dimer levels (135.7 µg/mL). Enhanced whole body computed tomography (CT) revealed fractures of the lamina at the second and third cervical vertebrai, right first rib, tenth thoracic vertebral body (compression type), second lumbar vertebral body (burst type) and right radius. Additionally, a thoracic aortic arch injury and intraabdominal fluid collection were noted. (Figure 1)

Immediate management included hypotensive rate control therapy using calcium and a beta blocker, targeting a systolic blood pressure of 80 mmHg for prevention of rupture of the aorta. Endovascular treatment was also selected for the aortic injury because of the presence of multiple injuries. On the day of his injury, the subject was restless and therefore was intubated using a sedative. On the fourth hospital day, he underwent deployment of a stent-graft into the aortic arch by an endovascular specialist who was invited from another hospital. The following day, he underwent posterior fixation of the lumbar burst fracture by the orthopedic surgeons and was extubated on the sixth hospital day. Follow up ultrasound and CT imaging showed that the fluid collection in his abdomen had resolved, so the subject was allowed to begin eating and also to begin inpatient rehabilitation including muscle strength training, balance training and ambulation training. Of note, rehabilitation was not the emphasis of this case report, thus, is not described in detail. After undergoing plate fixation for the radial frac-

Figure 1. Enhanced chest computed tomography (CT) on arrival. The CT scan shows pseudo-aneurysm at the aortic arch (arrow).
tured, he was discharged on the 28th hospital day to home, independently.

**DISCUSSION**

**Cause of injury**

By necropsy, approximately 10% of automobile accidents or falls from aircrafts result in fatal aortic injury, indicating that aortic injury must be considered in fatal high-energy accidents.6,7 Regarding the natural history of aortic injury, Parmley evaluated 296 cases of blunt aortic injury in young soldiers and found that about 15% survived long enough to get to a hospital.8 Of this 15%, 99% would have died without surgical intervention; 15% of these subjects would have survived only the first hour, 30% the first six hours, 49% the first 24 hours. Seventy-two percent would have died within eight days, and 90% within 4 months.8 The mechanism of blunt aortic injury remains the most important factor in establishing the diagnosis, with falls from over three meters representing a major source of this injury. During paragliding, pilots fly well over three meters from the ground, so falling while paragliding carries a risk of sustaining blunt aortic injury. In a previous report concerning fatal accidents due to paragliding, aortic injury was reported in addition to head, cervical cord injury, and lung rupture.3,5,9

Blunt trauma can damage the thoracic aorta by several mechanisms. The most commonly described cause of rupture is the differential forces set up within the chest by deceleration in either the horizontal or vertical plane.6,10 The descending aorta remains fixed to the posterior chest wall, while the heart and ascending aorta swing forward and tear free at the isthmus. Given that the present subject had thoracic and lumbar fractures, which are frequently induced by energy through the vertical plane, the aortic injury was presumably caused by a mainly vertical trauma due to a fall from a height.11 Aortic arch injury has been reported following a fall due to an airplane accident.7

**Signs and Symptoms of Aortic Arch Injury in the Prehospital Setting**

Some clinical features that suggest the presence of blunt thoracic aortic injury include hypotension, upper extremity hypertension, bilateral lower extremity pulse deficit, and initial chest tube output of >750 mL of blood.12 Patients with this presentation have a high incidence of other significant injuries. However, these clinical features are unreliable for diagnosis of aortic injury as their absence cannot exclude the presence of the blunt aortic injury.12 Thirty percent of patients with this injury have no external signs of chest trauma while 75% have rib fractures that draw attention away from the concomitant intrathoracic injury.12 The subject of the present case had chest pain due to rib fracture and multiple significant spinal injuries due to the high-energy accident, thus any first responder should have treated this case as a potential blunt thoracic aortic injury.

**Appropriate Care of the Victim in the Prehospital Setting**

A first responder treating a patient who sustained injury due to paragliding must consider some important key points. Michetti et al reported that overall mortality with aortic injury was 92% and prehospital mortality was 63%.13 Thus, first the provider should always consider the possibility of an aortic injury, which can be lethal. Second, the provider should address the patient’s airway, breathing, and circulatory status. If the patient goes into cardiac arrest, immediate basic life support must be provided, and the automated external defibrillator be used as indicated, after activating the emergency response system. Third, if able, induce hypotension by limiting prehospital intravenous fluid administration and using nitrates, which may result in increase of survival rates for this type of patient with a rupture of the aorta.14 Providing pain control and gentle treatment during stabilization so that he patient does not sustain an increase blood pressure. Finally, transport the patient to a trauma center as quickly as possible, as patients with aortic injury taken to a trauma center had significantly lower mortality than patients taken to a non-trauma medical center.13

**The Radiologic Findings Upon Hospital Admission**

The first examination is typically includes plain radiography. A widened mediastinum, blurred aortic contour, and irregular aortic arch may be visible on chest X-ray, and are typical image findings in cases
of thoracic aortic injury. However, the sensitivity of chest X-ray in the detection of aortic injuries is not high. Thus, additional imaging is warranted, and Computerized Tomography (CT) of the chest with intravenous contrast is strongly recommended for the diagnosis of clinically significant thoracic aortic injury. In the present subject, the chest X-ray only showed minor aortic arch irregularity; however, enhanced CT clearly demonstrated the greater extent of the aortic arch injury.

**REHABILITATION PLAN**

Before the repair of the aortic injury in the present case, the patient was strictly confined to bed because a rupture of the aortic injury had the potential to result in sudden death. In addition, the subject had sustained a lumbar burst fracture; thus, postural change was not allowed based on the instructions of the orthopedist. A pressure dispersing bed was used to prevent integumentary breakdown. After repairing the aortic injury, passive motion of upper extremities was started by nurses to prevent contracture. After the surgical stabilization of the lumbar fracture, postural change and passive motion of all extremities commenced (subject remained in a cervical orthosis) by nurses. After extubating the patient and confirming the disappearance of the fluid collection in his abdomen, physical therapy ensued to increase the subject’s, sitting balance, transfer abilities, standing balance and gait, and muscle strength. Each of these interventions was provided depending on recovery of the subject’s function and degree of pain. The rehabilitation program, which was determined based on thorough individualized assessment of his specific problems, allowed the patient to obtain functional ambulatory independence by the time that he was discharged.

**CONCLUSION**

A first responder or physicians should pay attention to the possibility of lethal aortic injury when treating patients who suffer falls while paragliding (or from substantial heights in other circumstances) and provide appropriate management. Although not common, such an injury could be life threatening and should be considered a priority in post-traumatic management.

**REFERENCES**


Superior capsule reconstruction is a recently-developed surgical technique for the treatment of massive, irreparable rotator cuff tears. So far, biomechanical cadaveric studies and clinical outcomes results have been promising concerning integrity, stability, and ROM after superior capsule reconstruction. As this technique has only been recently developed, an evidence-based rehabilitation protocol has not been previously designed. Thus, the purpose of this clinical commentary is to provide an overview of superior capsule reconstruction and to propose a rehabilitation program based on the available scientific evidence. The existing evidence is supplemented by the experience of the senior author who has performed more than forty superior capsule reconstruction procedures to date. This proposed rehabilitation protocol consists of four distinct phases, focusing on maximal protection, range of motion and muscular endurance, muscular strength and return to activity.

**Level of Evidence:** 5

**Key words:** Irreparable rotator cuff tears, rehabilitation, shoulder, superior capsule reconstruction

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INTRODUCTION AND BACKGROUND

The prevalence of massive rotator cuff tears has been reported to be as high as 40% of all rotator cuff tears.\(^1\,^2\) If not treated in a timely manner, muscle atrophy and fatty infiltration often ensue, resulting in irreparable tears.\(^3\) But even if treated in time, the failure rates of massive rotator cuff repairs are higher than those following the repair of smaller tears.\(^4\) Once a tear is irreparable, a spectrum of treatment options exists. Non-operative management may be indicated in patients with low demands and symptoms that occur predominantly with use, but it has been shown to lead to the progression of osteoarthritis.\(^5\,^6\) Partial rotator cuff repair and debridement have shown good results;\(^7\,^10\) however, there is limited long-term outcome data of 10 years or more to support its use, as well as the risk of continued pain, loss of motion and function, and worsening arthritic changes.\(^7\,^10\) In elderly patients with advanced shoulder osteoarthritis, reverse total shoulder arthroplasty may be indicated to address cuff tear arthropathy.\(^2\) However, limited implant longevity and activity restrictions from high-impact activities make joint replacement a less desirable option in younger patients. Therefore, additional options have been developed for younger patients. Latissimus dorsi tendon transfers have been shown to be a reasonable treatment method for posterosuperior massive rotator cuff tears. However, high complication rates, difficult revisions following failure, and poor outcomes in certain patient populations make stringent patient selection for this procedure particularly important.\(^11\)

Less invasive than latissimus dorsi tendon transfer, the superior capsule reconstruction (SCR) procedure is a novel technique developed in Japan by Mihata et al.\(^12\) as reverse arthroplasty was not approved in Japan at the time. The original technique used fascia lata autograft to reconstruct the superior capsule in the presence of an irreparable rotator cuff tear. Today, a number of allograft options, including a human acellular dermal allograft (Arthrex, Naples, FL), can be used instead of fascia lata autograft. As demonstrated both biomechanically and clinically by Mihata et al.,\(^12,\,13\) the graft design and surgical placement prevents the humeral head from migrating superiorly and thus enables efficient biomechanics of the shoulder. Additionally, the graft acts as a mechanical spacer between the humeral head and the undersurface of the acromion. Improved range of motion, joint space, and American Shoulder and Elbow Surgeons (ASES) scores following SCR have been reported.\(^13\) This arthroscopic technique has a low complication rate and short-term follow-up at a minimum of two years postoperatively shows limited progression of osteoarthritis and rotator cuff muscle atrophy.\(^13\)

As this innovative technique is only emerging from its infancy, an evidence-based rehabilitation protocol has not been previously designed since the technique was only developed in 2007.\(^12,\,14\) Therefore, the purpose of this clinical commentary is to provide an overview of SCR for the treatment of massive rotator cuff tears and to propose a rehabilitation program based on the available scientific evidence.

ANATOMY / BIOMECHANICS / PATHOBIOMECHANICS

Movement at the shoulder complex arises from a combination of glenohumeral and scapulothoracic motion. The scapula provides a muscle attachment site and allows load transfer from the upper limb to the thorax. The bony architecture, labrum, joint capsule, ligaments and negative pressure within the glenohumeral joint space all provide passive stability. In addition, the rotator cuff and long head of the biceps tendon center the humeral head on the glenoid and provide active stability, thereby allowing effective shoulder function. The rotator cuff consists of four muscles working synergistically: the supraspinatus, infraspinatus, teres minor, and subscapularis. Each muscle’s origin and insertion sites determine its function. The supraspinatus forms the superior aspect of the rotator cuff and initiates abduction. The infraspinatus and teres minor comprise the posterior aspect of the rotator cuff and contribute to abduction and function primarily to initiate external rotation. The subscapularis makes up the anterior portion of the rotator cuff and initiates internal rotation.

In healthy shoulders, a balanced force couple for the glenohumeral joint in both the coronal and the axial planes is maintained by the synergistic action of the deltoid and rotator cuff muscles. In the axial plane, the subscapularis and infraspinatus/teres minor complex maintain a balanced force couple, while the deltoid and rotator cuff inferior to the humeral head equator form a bal-
anced force couple in the coronal plane. As such, the rotator cuff muscles function as primary dynamic stabilizers to maintain concentric joint reduction during rotation of the humeral head on the glenoid.

Small to medium size rotator cuff tears involving the supraspinatus and the anterior portion of the infraspinatus do not affect stability in the coronal and axial planes because the balanced force couples are maintained. These can be differentiated from massive tears involving at least two tendons including the postero-inferior part of the rotator cuff where the balance of the force couple in the coronal plane is lost, thereby compromising the fulcrum that is necessary for normal glenohumeral mechanics.1,15-20

To restore normal kinematics in patients with massive tears of the postero-superior rotator cuff tendons, greater forces are required by both the deltoid and the intact rotator cuff muscle-tendon units, particularly the subscapularis, to achieve stable abduction.21 The progression of a rotator cuff tear leads to disruption of the axial force couple and subsequent superior subluxation of the humeral head and shoulder dysfunction.19 The force required to move the arm increases with tear size making the biomechanics less efficient. The tensile load on the intact fibers increases because the torn tendons cannot contribute to load sharing, and this leads to tear propagation, especially if the remaining tendon is of poor quality.

Additionally, with initiation of abduction, superior subluxation of the humeral head can occur as a result of muscle weakness or tendon retraction, leading to increased cuff impingement between the greater tuberosity and the inferior aspect of the acromion.16,22 This increased cuff impingement can cause medial extension of supraspinatus tears, leading to a cycle of superior humeral head migration and tear propagation. Usually, a massive rotator cuff tear involving at least two torn tendons is needed to provoke superior migration of the humeral head.23 Non-anatomical superior subluxation of the humeral head against the glenoid produces shear forces at the articular surfaces that cause cartilage destruction. Without early intervention, pain and loss of function ensue, along with the development of disabling osteoarthritis that often progresses to rotator cuff arthropathy.22

**SURGICAL TREATMENT**

Many operative procedures, including those previously outlined, have been used to treat massive rotator cuff tears, but this commentary focuses on SCR (Figure 1) of which the senior author has performed more than 40 to date. The arthroscopic SCR technique has previously been described in detail by Katthagen et al.24 The retracted, deficient supraspinatus tendon is arthroscopically confirmed and extensively debrided. After the superior glenoid and greater tuberosity bony surfaces are prepared, three anchors are inserted into the glenoid at the 10, 12, and 2 o’clock positions. The rotator cuff defect is measured to determine the size of the human acellular dermal allograft. The patch is then introduced into the shoulder through the anterolateral portal, and the graft is fixed medially. On the humeral side, two anchors are inserted for medial-row fixation at the articular cartilage margin. Two lateral anchors are then inserted for lateral-row fixation. Finally, the lateral part of the graft is compressed down onto the footprint using a suture bridge technique (Figure 2). The native rotator cuff tissue may require margin convergence and is then sutured into the graft for additional stability.

**POST-OPERATIVE REHABILITATION**

Post-operative rehabilitation following SCR begins with close communication between the surgeon...
Phase I – Maximal Protection

The rehabilitation goals of Phase I include protecting the surgical repair, minimizing pain and inflammation, maintaining mobility of accessory joints and providing patient education. Physical therapy typically begins on post-operative day one in order to review post-operative restrictions and precautions, rehab protocol and progressions, and initial home exercise program, as well as to discuss expected functional outcomes.

Post-operatively, patients are immobilized in a sling limiting passive range of motion (PROM) as much as possible. This is in order to protect the surgical repair by allowing sufficient time for healing to occur prior to introducing controlled, progressive load to the graft. The patient is placed in a sling with abduction pillow to support the glenohumeral joint in the scapular plane, which is worn for six weeks. Patients are instructed to wear compression stockings for two weeks and to perform ankle pumps for up to six weeks post-operatively in order to reduce the risk of deep vein thrombosis.

Although the patient is not initially allowed PROM of the glenohumeral (GH) joint, it is important to ensure maintenance of accessory joint mobility throughout the six-week immobilization period of the shoulder. Patients are instructed on proper performance of active range of motion (AROM) of the cervical spine as well as AROM of the elbow, wrist and hand outside of the sling. Concurrent scapular retraction and depression is also initiated at this time in order to facilitate activation of postural musculature and prevent tightness of the anterior shoulder musculature. Patients are also encouraged to perform gentle ball squeezes using the hand on the involved side in order to facilitate circulation throughout the upper extremity while immobilized in the sling.

Instruction is provided to the patient and caregiver, if present, regarding donning/doffing of the sling as well as how to properly don and doff clothing. It is recommended that patients use a second sling to support their shoulders while showering. Five to six times daily, patients are encouraged to apply range of motion exercises with scapular stabilization for the first eight weeks.

Figure 2. Arthroscopic photograph in a left shoulder taken from the lateral portal, showing the final SCR construct.
cryotherapy and compression for no more than 30 minutes to the involved shoulder the first two weeks post-operatively in order to assist with minimizing pain and inflammation and to provide comfort while sleeping.26

Phase II – Range of Motion and Muscular Endurance

The range-of-motion (ROM) and muscular endurance phase is typically introduced 6 weeks post-operatively. The rehabilitation goals of Phase II consist of restoring passive and active range of motion while managing pain, improving rotator cuff endurance, establishing normal scapulohumeral rhythm and returning to light functional activities of daily living.

Following six weeks of immobilization, the patient is cleared by the surgeon to begin restoring full PROM and AROM of the GH joint without restrictions other than patient tolerance. Rehabilitation of the shoulder at this point generally follows a rehabilitation program typical of a post-operative massive rotator cuff repair. This includes both healing timelines and criteria-based progression as outlined by the multi-disciplinary Level V consensus statement by Thigpen et al.27 allowing for special considerations specific to SCR rehabilitation. It is important to remember the SCR procedure is indicated for massive, irreparable rotator cuff tears in select patients with a functioning deltoid and at least a partially functioning subscapularis and that not all rotator cuff musculature is repaired with this procedure. Moreover, the patient who has undergone SCR may not meet the criteria for rehabilitation progression at the same rate as a patient who has undergone a rotator cuff repair.

Most candidates for SCR present pre-surgically with a retracted, full thickness tear of the supraspinatus and a partial- to full-thickness tear of the infraspinatus and teres minor. Emphasis should be placed on muscle activation of the deltoid, specifically the middle and posterior fibers, along with regaining as much external rotation function as possible. The external rotators of the glenohumeral joint may be difficult to activate initially, and activation is dependent upon the amount and tissue integrity of the retracted infraspinatus/teres minor surgically attached to the superior capsule graft. Along with the superior capsule graft, the deltoid and internal and external rotation musculature make up the primary force couples about the glenohumeral joint.28 Force couples result in rotational movement; the balance of muscular forces creates dynamic stabilization of the glenohumeral joint through humeral head compression.28 The graft will prevent superior migration of the humeral head during active elevation of the glenohumeral joint. The deltoid and internal/external rotation musculature provide the force couple to approximate the humeral head in the glenoid throughout active and resisted range of motion.

Pain-free glenohumeral PROM is initiated in the supine position prior to beginning active assisted range of motion (AAROM), which typically commences during the seventh post-operative week if PROM is progressing appropriately and pain is properly managed. Generally, AAROM is initiated in positions that place less gravitational demand on the musculature, such as supine, prone or side-lying positions, and can be progressed to seated or standing positions as tolerated. PROM and AAROM exercises should focus on planes of glenohumeral motion including forward elevation, scaption, and internal and external rotation. Supine AAROM forward elevation to 90° and external rotation are initiated utilizing a dowel or the contralateral upper extremity for assistance. Based on the authors’ experience, a slideboard can also be utilized in the supine (Figure 1), side-lying, or prone (Figure 2) positions in order to facilitate deltoid activation with scaption and forward elevation movements. Open chain proprioception, pendulums (i.e. Codman’s exercise) and gentle aquatic therapy can also be initiated at this time in accordance with patient comfort. Emphasis should be placed on maintaining scapular control with all AAROM and AROM therapeutic exercises.

Scapular and glenohumeral isometrics, as well as initial proprioceptive therapeutic exercises, should be incorporated into treatment at this time as the patient is just beginning to re-learn muscle activation patterns associated with movement of the glenohumeral joint. Sub-maximal glenohumeral isometrics should include the deltoid, subscapularis, infraspinatus, teres minor, triceps and biceps. Isometrics are initiated in a supine, neutral scaption position and can be progressed to varying degrees of abduction, forward elevation, and external rotation.
Biofeedback may be useful with isometrics in order to facilitate neuromuscular re-education of the external rotators. Scapular isometrics are progressed from initial activation in Phase 1 to side-lying or prone positions and should focus on retraction, protraction, depression and elevation from a neutral scapular position. These exercises should begin without resistance before progressing to the application of manual resistance, which provides effective biofeedback regarding scapular proprioception. Progression of scapular isometrics in a side-lying or prone position can be performed with the upper extremity supported in various degrees of external rotation or scaption.

When the patient exhibits effective isometric muscle contraction as well as fair muscle activation with AAROM therapeutic exercises with pain managed effectively, AROM is then initiated. AROM is typically incorporated into treatment one to two weeks after the initiation of PROM, per proper progression of PROM/AAROM and adequate pain control. PROM and AAROM should be incorporated into physical therapy sessions as needed in conjunction with AROM in order to restore functional range of motion. Sling use is also discontinued at this time via a gradual progressive weaning process, and patients can begin utilizing the upper extremity with light activities of daily living, typically at and below waist level. AROM is generally initiated in a supine position. Modifications may be necessary based on each individual's progression at this point in their rehabilitation, and side-lying (Figures 3 and 4) and prone (Figure 5) positions may be utilized prior to progression to standing and seated positions as neuromuscular control and endurance improves. The following exercises have been indicated in the literature to produce the highest electromyographic
(EMG) activity of the rotator cuff musculature without compensation of larger muscle groups. These exercises may require modification based on each patient's ability to recruit the proper musculature following SCR. Biofeedback can be a beneficial tool to improve functional neuromuscular re-education of the rotator cuff, deltoid, and periscapular musculature in this phase of rehabilitation.

Regarding external rotation of the glenohumeral joint, side-lying external rotation and prone external rotation abduction exercises have been documented to provide the highest EMG activation of the infraspinatus. Side-lying external rotation with a towel roll in the axilla should be trialed first, as prone external rotation abduction exercises may place excessive tensile load on the repaired tissue due to insufficient muscular strength to perform these exercises effectively. The towel roll places the glenohumeral joint in the scapular plane, which facilitates an adduction moment upon the glenohumeral joint, thereby reducing capsular stress, improving scapular stability and increasing EMG activity of the targeted musculature. Initially, patients will lack sufficient strength to move through the available range of motion. The physical therapist can begin with manual placement of the glenohumeral joint in various degrees of external rotation and have the patient perform isometric holds. Alternatively, gentle rhythmic stabilization may also be utilized. The glenohumeral joint can also be placed at the end range of available external rotation following isometric holds allowing the patient to perform the eccentric portion of the exercise by returning the arm to neutral. Active external rotation can also be performed in a seated position utilizing a slideboard for assistance as needed. Keep in mind the potential limited range of motion with this movement based on each patient's pre-surgical level of function, the availability and integrity of salvageable external rotator cuff tissue.

The subscapularis and pectoralis musculature work in concert with the external rotation musculature to establish the internal/external rotator force couple that functions in concert with the deltoid. Subscapularis activation is initially facilitated with isometrics and external rotation exercises. Alizadehkhaiyat et al. reported increased EMG activity of the subscapularis with prone external rotation and horizontal abduction exercises. Deltoid function is imperative following SCR to restore the force couples about the glenohumeral joint. Initially, the deltoid should be activated utilizing multi-angle submaximal isometrics prior to progressing to isotonics. It is beneficial to begin deltoid isotonics with the patient in a side-lying (Figures 3 and 4) or supine (Figure 1) position. Patients can begin in a side-lying position to perform glenohumeral abduction in the coronal plane of the
body (Figure 3), as well as horizontal abduction in the transverse plane (Figures 4 and 5). Assisted scaption exercises performed on a slideboard with the patient prone (Figure 2) or supine (Figure 1) are beneficial to facilitate deltoid function in a functional position without excess gravitational resistance prior to progressing to seated or standing scaption exercises.

The prone full-can exercise has been proven to generate good electromyographic activity of the posterior deltoid and the lower trapezius.35, 36 This exercise may need to be performed with slideboard assistance prior to performing it unassisted in a prone position, with the final progression to an upright position. Another option to promote functional re-training of the deltoid is the patient performing a press to 90° of glenohumeral forward elevation in a supine position (Figure 6), and subsequently progressing to an incline press. The aforementioned exercises facilitate concentric and eccentric muscular endurance of the posterior, middle, and anterior portions of the deltoid. Isotonic external rotation exercises of the glenohumeral joint, as described above, also promote activation of the posterior deltoid.

The serratus anterior, which protracts the scapula, plays a crucial role in establishing normal scapulo-humeral rhythm and is an integral component of establishing glenohumeral motion above 90°. Serratus anterior isotonics can be performed initially in a supine or prone position with the glenohumeral joint at 90° of forward elevation while performing the serratus “plus” exercise to protract the scapula while maintaining a static glenohumeral position. Emphasis is placed on proper protraction and retraction to the neutral position of the scapula at 90°, progressing to scapular protraction at various angles of forward elevation and/or scaption in conjunction with the progression to upright positions while promoting neuromuscular control of the glenohumeral joint. Open chain scapular exercise is emphasized during this phase of rehabilitation in order to establish proper scapulothoracic force couples and improve neuromuscular endurance with AROM activities. Closed chain scapular exercise is initiated during Phase III of the rehabilitation process in order to allow sufficient time to develop proper dynamic stability prior to the initiation of compressive forces on the glenohumeral joint.

Establishing scapular stability is imperative to normalize scapulo-humeral rhythm to promote optimal function following SCR. Scapular control is initiated in Phase I and is progressed during Phase II by
emphasizing proper scapular position, neuromuscular control, and endurance of the serratus anterior, rhomboids, and middle and lower trapezius muscles throughout all AROM exercises while reducing upper trapezius compensation patterns. It is important to establish normal scapulohumeral rhythm with AROM prior to the initiation of resisted ROM in order to promote proper muscle activation and to reduce compensation patterns. Manual therapy techniques can also be utilized throughout this phase as indicated, keeping in mind the repaired tissues and healing timelines. Manual techniques include but are not limited to soft tissue mobilization, joint mobilizations, contract/relax techniques and low load, long duration stretching. These techniques should be appropriately selected to improve mobility and/or decrease pain.

This phase of rehabilitation can potentially require a significant amount of time to properly retrain the remaining rotator cuff musculature, deltoid, and periscapular musculature to function in concert with the superior capsule graft. The level of function exhibited by each patient prior to surgery should be taken into consideration. Massive, chronic rotator cuff tears generally take an extended duration of time to rehabilitate, regardless of the type of surgical intervention performed.

**Phase III – Muscular Strength**

The muscular strength phase is generally introduced at 10-12 weeks postoperatively and consists of progressive resisted ROM and the initiation of closed chain exercises. The rehabilitation goals of phase III include advancement of strength and restoration of functional ROM, progressing to higher level functional activities.

Strengthening should be initiated with light resistance bands and/or light dumbbell isotonics, and the initiation of closed chain stabilization exercises should incorporate light weights or resistance and have a functional basis. All resisted exercises should be performed with the underlying goal of improving functional ROM and strength, while ensuring normal scapulohumeral rhythm is maintained.

Resistance is initially applied with the addition of light dumbbells or light resistance bands to the non-resisted isotonic exercises previously described in Phase II. Resistance band exercises, which provide concentric and eccentric components, can be incorporated below shoulder level in the scapular plane at this time. Patients may not be able to perform full active motion initially with the addition of resistance; therefore, initial band strengthening may consist of isometric holds or require modified positions for optimal muscle activation without compensation. The internal and external rotators of the glenohumeral joint are commonly strengthened in a standing position with a towel roll under the arm to place the glenohumeral joint in a neutral scaption position. Forward punches to 90° of glenohumeral forward elevation with a “plus” are utilized to promote strengthening of the serratus anterior and for functional strength above waist level (Figures 7 and 8). These may need to be initiated in a seated assisted position prior to tran-
Proprioceptive exercises are also progressed within this phase with the addition of a TheraBand™ FlexBar® (Performance Health, Akron, OH, USA), resistance band, or manual perturbations in various functional positions beginning below shoulder height in the scapular plane, progressing to shoulder height as appropriate. Initial closed kinetic chain exercises are also Initiated to improve neuromuscular control, muscular strength and proprioception of the glenohumeral joint. Closed chain exercises are typically initiated in a low load position while standing with hands on a wall, to standing. Resisted rows are also commenced at this time, beginning first in a prone position with light dumbbells prior to transitioning to standing position with resistance bands. Resisted biceps and triceps exercises can also be incorporated at this time with either light dumbbell or band resistance, progressing as appropriate. Resisted exercises can be progressed to shoulder height and above as tolerated by the patient. It is imperative to emphasize proper scapular position in order to maintain proper glenohumeral kinematics with the addition of the resisted load.

Figure 8. Forward elevation with resistance band to facilitate external rotation.

Figure 9. Seated, assisted forward elevation with external rotation resistance.
progressing to a declined or quadruped position. Plank positions on the floor may be too demanding at this time secondary to strength deficits for patients who have undergone SCR. Initial closed chain activities consist of weight shifts, scapular protraction/retraction “plus,” static holds with and without manual perturbations, double arm to single arm support, and shallow push-ups if appropriate. It is important to consider the functional deficits of each patient when prescribing specific exercises, ensuring they are appropriate for and relate to established functional goals.

This is typically the final phase of rehab prior to discharge from physical therapy depending on each patient's functional requirements for daily activities, work and recreational activities. Physical therapists should expect to spend an extended duration of time in this phase of rehabilitation for patients who have undergone SCR as compared to those who have undergone massive rotator cuff repair. Patients who do not require high levels of overhead function and exhibit sufficient strength may begin to return to full daily activities and recreational activities below shoulder level. Patients whose activities demand a higher level of function from the shoulder, including repetitive or overhead activities, may find themselves limited initially as preliminary outcome studies following SCR indicate functional improvements up to two years postoperatively.13

Phase IV – Advanced Strength and Return to Activity

This phase of rehabilitation typically consists of overhead strengthening, advanced closed chain, proprioceptive and plyometric exercises. Based on the functional status and strength achieved at this point post-operatively, patients may or may not be appropriate for this phase of rehabilitation. The physical therapist should focus on specific functional requirements based on strength deficits.

As patients continue to build strength, treatment should focus on progressing endurance with high-exertion daily activities as well as work and recreational activities at or below shoulder height. It may be challenging for patients who undergo SCR to return to work activities requiring heavy lifting or repetitive overhead lifting as they may not demonstrate sufficient strength to support these types of activities. Return to higher level overhead sports may also prove difficult, and patients may not be able to achieve sufficient muscular power required for these types of activities. Physical therapists and patients can instead focus on recreational activities performed at or below shoulder height, including but not limited to cycling, shooting and golfing.

CONCLUSION

This clinical commentary describes a rehabilitation protocol following superior capsule reconstruction.
Post-operative rehabilitation begins with close communication between the surgeon, the patient, and the physical therapy team. A review of surgical findings is mandatory to establish rehabilitation guidelines. Once post-operative restrictions have been established, a rehabilitation protocol is customized based on surgical findings and patient goals. The standard protocol is characterized by four phases and starts with restrictions on movement lasting six weeks. The aim is to minimize stress placed on the implanted graft to facilitate early graft-to-bone healing. Afterwards, Phase II starts with restoring passive and active range of motion, managing pain, and improving endurance of the rotator cuff. Phase III consists of advancement of strength and functional restoration of ROM followed by Phase IV consisting of overhead strengthening, advanced closed chain, proprioceptive and plyometric exercises, as appropriate.

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ABSTRACT

Patellar instability is a common problem seen by physical therapists, athletic trainers and orthopedic surgeons. Although following an acute dislocation, conservative rehabilitation is usually the first line of defense; refractory cases exist that may require surgical intervention. Substantial progress has been made in the understanding of the medial patellofemoral ligament (MPFL) and its role as the primary stabilizer to lateral patellar displacement. Medial patellofemoral ligament disruption is now considered to be the essential lesion following acute patellar dislocation due to significantly high numbers of ruptures following this injury. Evidence is now mounting that demonstrates the benefits of early reconstruction with a variety of techniques. Recently rehabilitation has become more robust and progressive due to our better understanding of soft tissue reconstruction and repair techniques. The purpose of this manuscript is to describe the etiology of patellar instability, the anatomy and biomechanics and examination of patellofemoral instability, and to describe surgical intervention and rehabilitation following MPFL rupture.

Key words: Knee, patellar instability, rehabilitation, surgery

Level of Evidence: 5
BACKGROUND AND PURPOSE
Patellar instability is a common complaint seen by physical therapists, athletic trainers and surgeons. Patellar instability in athletes is a general umbrella term used for either patellar subluxation or dislocation. Dislocation and subluxations can occur due to repetitive micro trauma over time creating a gradual progression of instability of a chronic nature. However, instability can also occur due to an acute event such as a patellar dislocation in which localized trauma has forced the patella laterally out of the safe confines of the patellar trochlea of the distal femur. Lateral patellar dislocations are the most common knee dislocation injury among young adults. One structure that helps maintain patellar stability is the medial patellofemoral ligament (MPFL). Substantial progress has been made in the understanding of the MPFL and its role as the primary stabilizer to lateral patellar displacement. MPFL disruption is now considered to be the essential lesion following acute patellar dislocation due to significantly high numbers of ruptures following this injury. Evidence is now mounting that demonstrates the benefits of early reconstruction with a variety of techniques.

Actual dislocations of the patella represent a sparse 2%-3% of all knee injuries. Historically these injuries have occurred more commonly in females than in males. Nonoperative treatment has been recommended for this injury, however, conservative treatment of this condition is often of little value as recurrent dislocation occurs in up to 15% to 44% of patients who have sustained a traumatic patellar dislocation. In persons who have had two prior episodes of dislocations the recurrence rate jumps to 49%. Maenpaa and Lehto report that in more than half of the patients, a first time patellar dislocation left untreated or treated nonoperatively will lead to instability and recurrent dislocations. These findings are similar to those of McManus et al who report that the natural history of a nonoperatively treated patellar dislocation involves re-dislocation in one of six cases; other residual symptoms in two of six, and three of six cases will be asymptomatic. Collectively these studies indicate that conservative treatment with a period of immobilization followed by physical therapy is associated with re-dislocation rates of upwards of 63%. Those who do not re-dislocate may continue to have persistent patellofemoral problems and disability and even femoropatellar osteoarthritis. Risk factors for recurrent instability include young age, immature physes, sports-related injuries, patella alta and trochlear dysplasia. Other predisposing factors that can contribute to chronic patellar instability include: femoral anteverision, external tibial torsion, genu valgum, patellar dysplasia, vastus medialis obliquus atrophy, pes planus, and generalized ligamentous laxity.

Patellar instability can be the result of multiple problems including structural anatomical abnormalities, or insufficient soft tissue restraints. Examples of structural abnormalities and insufficient soft tissue restraints include vastus medialis weakness, tight lateral structures such as the tensor fascia lata/iliotibial band, and lateral retinaculum. Other anatomical variations that can create this multifactorial problem include patella alta, increased quadriceps angle, excessive tibial tubercle-trochlear groove distance, trochlear dysplasia and ligament hyperlaxity. The purpose of this manuscript is to describe the etiology of patellar instability, the anatomy and biomechanics and examination of patellofemoral instability, and to describe surgical intervention and rehabilitation following MPFL rupture.

ANATOMY
Patellar stability is afforded by both active and passive restraints. Active restraints to the anterior knee are the quadriceps muscle group. Both the rectus femoris and the vastus intermedius have a direct line of pull along the long axis of the femur. The vastus lateralis and the vastus medialis both have, although at slightly different angles, an oblique insertion onto the patella which allows for medial and lateral patellar stabilization. Collectively these muscles provide dynamic patellofemoral stability. Passive patellar stability is provided by several soft tissue structures including the patellar tendon and the patellar retinaculum. The patellar tendon is the distal component of the quadriceps tendon. The patellar retinaculum is different on the lateral and medial sides. The lateral complex is more intricate and includes two different structures: the superficial oblique retinaculum and the deep transverse retinaculum. The medial side of the retinacular
structures are quite different and include the medial meniscopatellar ligament and the MPFL. In the three-layer description of the medial side of the knee, the MPFL lies in the second layer. The MPFL was originally thought to be present in only 29%-89% of knees. It is now commonly accepted that this structure is present in all knees and that it is the major medial static stabilizer of the patellofemoral joint.

The MPFL is unique in that the anterior portion interdigitates with the deep fibers of the vastus medialis obliquus (VMO) (Figure 1), suggesting that it might work together with the VMO supplying medial stabilization. The VMO is the oblique, medial portion of the quadriceps that is thought to provide dynamic medial patellofemoral restraint. In concert these two structures appear to draw the patella from its slightly lateralized position in full extension, moving the patella medially toward the trochlea such that the patella enters the trochlea during early knee flexion movements.

The anatomical origin of the MPFL has been described in multiple locations. Warren and Marshall report that the MPFL is located at the region of the superficial medial collateral ligament. Feller and colleagues report it to be anterior to the medial epicondyle. Steensen describes the origin as the actual anterior medial epicondyle, while multiple authors report that its origin is simply at the medial epicondyle.

BIOMECHANICS
Numerous studies have examined the biomechanical contributions and restraint provided by the MPFL. Amis has shown that the native MPFL is not a very robust ligament; when compared to others in the knee it only withstands loads of about 208N when tested to failure at 25 mm of displacement. The MPFL provides from 50-60% of the restraint to lateral patellar translation during the ranges of 0-30 degrees of knee flexion. If the MPFL is sectioned, the patella displaces laterally, even with the other medial stabilizers intact. Amis and colleagues suggest that this ligament is tightest near full extension and loses tension as the knee is flexed. However, McCulloch et al report that the actual highest increase in strain occurred between 25-30 degrees of knee flexion. This may be biomechanically appropriate as the patella generally enters the trochlea near 15-20 degree of knee flexion and thus has improved bony support and congruence in that range and further into flexion.

The MPFL rupture at a mean elongation of 26 +/-7 mm in cadaveric specimens. Because the mean length of the MPFL is 53 mm, ruptures occur at approximately 49% strain. The average width of the MPFL is 1.9 cm.

TEAR CLASSIFICATION
Nomura described a classification for tears based on surgical findings from 67 knees following acute or recurrent patellar dislocation. Focal injury was seen in 17/18 knees with acute patellar dislocation. These injuries were categorized into Type I and Type II injuries. Type I are avulsion type or detachments of the ligament from its femoral attachment. Type II injuries are intra-substance tears of the ligament. The location of these intra-substance tears was usually near the normal femoral attachment of the ligament. In all knees with recurrent patellar dislocation the MPFL was abnormal. Abnormality was
described as three different types: Type I included no MPFL injury that was seen by gross inspection, but ligament was loose at its femoral attachment; Type II consisted of scar tissue either in the body of the MPFL or between the ligament and its femoral attachment (but both are loose); Type III was termed “absent” type, in which the ligament consisted of a remnant that lacked continuity or could not be identified.

**HISTORY**
As with most knee conditions, obtaining a subjective medical history is critical to the success of any evaluation of musculoskeletal injuries and is never more important than in the knee. The medical history should be performed in a consistent and orderly fashion with every patient in order to obtain crucial information without missing important findings. Most patients will tell you their problems if you listen closely and ask the appropriate questions. Acute traumatic patellar dislocation can occur due to a single inciting incident; however subluxation of the patella may occur as recurrent patellar instability due to repetitive minor trauma. In some instances there may not be a blow to the knee during the injury mechanism. In general, patellar dislocations or subluxations occur in the lateral direction however, although rare, medial displacement can also occur. In most cases these injuries are the result of a noncontact, quick turning incident, in a single direction with the femur and tibia moving in opposite directions. This can occur during a plant and cut maneuver or trying to fake someone out quickly, in which the femur internally rotates while the tibia remains relatively externally rotated. Regardless of the mechanism, the athlete almost always feels a vivid sensation of bony subluxation. The patient may describe the patella’s position grossly laterally or just a medial prominence. Do not be fooled, as the medial prominence may actually be the uncovered medial femoral condyle that can clearly be seen due the laterally displaced patella. The laterally displaced patella will stay displaced as long as the knee remains flexed. With the help of a sports physician, athletic trainer or therapist movement of the knee into extension will usually cause an abrupt relocation, with which a “clunk” or shifting sensation is felt, providing significant pain relief. Historically a first time acute patellar dislocation results in significant effusion in the knee. In the athlete with a chronic recurrent dislocation the swelling and effusion may be much more subtle.

**EXAMINATION**

**General Examination**
Any evaluation of a knee disorder should be performed with the patient dressed in shorts with the knees clearly exposed. Physical examination of patellar instability can be done in the face of an acute dislocation, which will be done completely different than that of the athlete with a more chronic condition. Pending the time frame between dislocation and examination the patella may still be dislocated and displaced laterally. Just because the patella presents in its correct position it cannot be assumed that it was not dislocated previously. Within several hours of an acute dislocation, a significant effusion will be present. This may limit the ability to perform a thorough examination due to limited knee mobility due to swelling. There will likely be tenderness along the medial retinaculum, the MPFL and the adductor tubercle. With these described symptoms it is best to assume that the patella has been dislocated until proven otherwise. Swelling, range of knee motion, palpation, and the amount of passive patellar mobility should always be compared to the uninvolved side. A more complete physical examination can be performed on the suspected recurrent patellar dislocation patient as they will not be as irritable as the patient with an acutely dislocated patella.

**STANDING EXAMINATION**
In the standing position the patient should be assessed for multiple things. Equality of weight bearing can be easily viewed in this position, as can varus and valgus alignment. An athlete with miserable malalignment syndrome (MMS) can be predisposed to patellar instability. MMS is a constellation of several functional deformities which include internal rotation of the femur, with accompanied bayonet deformity of the tibia, external tibial torsion, and pronated feet. Due to significant swelling, and because maximal capsular volume of the knee is in 25-30 degrees of knee flexion, the patient may stand or walk with the knee in a flexed position.
SEATED EXAMINATION

The seated examination allows the clinician to view the knee in resting position from anterior, medial and lateral aspect. Where is the patella sitting passively in a relaxed seated position? In a patient with a large degree of patella alta the patella will be resting high and laterally in what is called "grasshopper eyes" position. Patella alta can be determined by an Insall-Savant measurement of greater than 1:1 ratio of patellar tendon length to patellar height. If the length of the patellar tendon is greater than the height of the patella a patella alta exists. This may predispose the athlete to recurrent patellar subluxations or dislocations due to excessive patellar tendon length.

The tibial tubercle sulcus angle can be measured with the athlete sitting over the edge of the treatment table with the knee flexed 90 degrees. The clinician observes the position of the tibial tubercle relative to the patellar center. The first line, a vertical line drawn from the center of the patella while the second is drawn from the center of the patella to the tibial tubercle. The tibial tubercle should be within the femoral trochlea when the knee is flexed 90 degrees. Controversy exists on what a normal angle shoulder be, as ranges from 0 degrees to 10 degrees have been reported.

Passive and active patellar tracking can also be assessed in the seated position. The tripod position, (leaning backwards slightly supported by both hands with a slight posterior pelvic tilt) is assumed to decrease hamstring tightness during testing. The clinician passively extends the relaxed patients knee from flexion to full extension. During this movement the patella translates from a slightly lateral position in flexion to a medial position as the knee extends, and eventually back laterally again near full extension. Slight variations sometime exist between individuals and even between right and left knees of the same individual, so small deviations should not be of great concern. As this is a passive test, it assesses osseous and non-contractive tissues. Excessive lateral gliding usually indicates tightness of the superficial retinacular fibers, whereas excessive tilting would indicate excessive deep retinacular restraint. Following performance of the passive portion of this test, the clinician should examine an active component by having the athlete actively extend their knee fully. A similar type of movement should be seen if passive patellar tracking is normal. The clinician should watch for an abrupt lateral displacement between the range of 20-30 degrees of flexion to full extension as the patella is deviated or subluxed laterally. This may be indicative of a dysfunctional vastus medialis obliquis muscle lacking dynamic medial stability.

Strength can be tested via manual muscle testing of the quadriceps and hamstring muscle groups while seated. Manual muscle testing of hip muscles can be done in supine, side lying and prone. Adequate strength of all hip muscles and musculature of the trunk/core is needed to ensure proper proximal control.

SUPINE EXAMINATION

Supine examination includes examination of passive patellar mobility, knee swelling and effusion and manual muscle testing of proximal hip musculature. Assessment of passive patellar mobility is done in slight (20-30 degrees) of knee flexion, to engage the trochlea. The patella is then passively translated in both the medial and lateral directions in the frontal plane (Figure 2). Patellar mobility is described in quadrants of movement. The width of the entire patella is four quadrants. Thus two quadrants of movement would indicate movement that is equal to half the patella’s width. Normal patellar mobility is from 1-3 quadrants of passive movement in either direction. Less than 1 quadrant of passive movement demonstrates hypomobility while passive movement greater than 3 quadrants demonstrates hypermobility. Following MPFL reconstruction passive mobility of 2 quadrants is desirable in the medial and lateral directions.

Swelling and joint effusion should be measured in all patients complaining of knee pain. Circumferential measurements can be taken at several different spots around the knee; In particular, measuring at the joint line is suggested for generalized joint effusion. An additional location in a patient with suspected patellar instability would be at an area approximately 10 cm proximal to the knee joint which is the area around the vastus medialis oblique which may be selectively atrophied due to pain and inhibition from knee pain.
INDICATIONS FOR SURGERY
Conservative treatment is universally attempted in an effort to strengthen the dynamic stabilizers of the anterior knee. When non-operative rehabilitation does not offer a satisfactory outcome regarding stability, surgical reconstruction of the MPFL may be offered. MPFL reconstruction has been shown to be an acceptable method to restore static stabilizing structures. Historically traditional procedures to address patellar dysfunction such as medial retinacular reefing or the lateral release have been utilized to address chronic patellar instability but these often result in continued instability, anterior knee pain, and even medial patellar instability due to iatrogenic causes. Indications for MPFL reconstruction include recurrent patellar instability that has failed standard nonoperative management. The role of MPFL reconstruction for acute patellar dislocation and isolated trochlear dysplasia has not been clearly determined as of the publication of this manuscript.

SURGICAL TECHNIQUE
Surgical reconstruction of the MPFL is performed in the following steps. A thorough examination under anesthesia is performed to assess ligament stability and evaluate the mobility of the patella with special attention to the lateral glide. This is checked both in extension (Figure 3) and in flexion (Figure 4).

Diagnostic arthroscopy is performed to evaluate the patellofemoral articular surfaces evaluating for any chondral damage and treating as indicated (Figure 5). Patellar articular surface injury may require debridement of loose cartilage or if severe may require a osteochondral repair type procedure in addition to the MPFL reconstruction.

Reconstruction of the MPFL should attempt to reproduce the native ligament, restore normal anatomy and function and is designed as a “check rein”, but is not intended to be used as a harness to hold the patella centered in the trochlea. Multiple autograft choices exist including: a hamstring

Figure 2. Examination of passive patellar mobility. A) The examiner uses thumb to determine midline of patella to determine amount of translation, B) translation of the patella in the lateral direction assessing the amount of passive patellar mobility. Following MPFL reconstruction the desired amount of passive patellar mobility should be approximately 2 quadrants or half the width of the patella.

Figure 3. Pre-operative lateral patellar displacement with knee positioned in flexion. Taken from: Manske RC, Lehecka BJ, Prohaska D. Medial patellofemoral ligament reconstruction for patellar instability. SPTS Home Study Course, Indianapolis, IN. 2010.
tendon,43,45 the adductor magnus,51,52 a portion of the quadriceps tendon,53,54 or a medial strip of the quadriceps tendon. Each of these can be used leaving the patellar attachment intact. Allograft tissue has been used, with outcomes that are acceptable, including no undue risk for re-rupture, and no donor site morbidity.55,56

The graft is secured to the patella either by tunnels passing the graft through the patella and anchoring on the far side or with an interference screw, or by looping the graft through the patella with no actual fixation in the patella itself. A double incision is used for proper tunnel and graft placement (Figure 6). When using hamstring autografts, the hamstring tendons must first be isolated and procured (Figure 7). The graft is passed between the soft tissue layers from the patella to its position of attachment on the medial femoral condyle making sure that the graft stays outside the knee capsule.
It is important to use bony landmarks and often fluoroscopy is employed to ensure that the graft entrance to the femur is in the correct location. After fixation of the graft, tension is set so that there is no excessive strain on the medial side of the knee (Figure 8). The knee is taken through full range of motion to ensure that the graft does not change in length and tighten or loosen. For example, if the femoral site is too proximal, the graft will be tight in flexion, and so the tunnel needs to be repositioned. Failure to change the tunnel may lead to a knee that has excessive loss of flexion after reconstruction. Following graft fixation, lateral patellar translation is again assessed to ensure proper tension (Figure 9).

Fixation on the femur can be done with interference screw, anchors in bone, or distal button fixation.

Post operatively the knee is placed in a compressive soft dressing and cold therapy is utilized. Surgery is done on an outpatient basis.

**PHASE I: PROTECTIVE PHASE (DAY 1 TO WEEK 6)**

Goals for this initial phase following reconstruction include protecting the repair, decreasing pain and inflammation, preventing the negative effects of immobilization, restoring knee range of motion and arthrokinematics, preventing hypomobility, promoting dynamic stability, preventing reflex inhibition and secondary muscle atrophy, developing neuromuscular control of the knee and maintaining core stability.

When MPFL reconstruction is performed independently, Phase I begins within 2-3 days of the surgery. This surgical procedure can also be performed concomitantly with a lateral release or distal...
realignment procedure and may require additional immobilization periods.

With isolated MPFL reconstruction, ambulation is weight bearing as tolerated and range of motion is progressed as tolerated immediately. Strict immobilization of the knee can result in loss of ground substance and dehydration and approximation of embedded fibers in the extracellular matrix of soft tissues.\textsuperscript{36} Because the surgical reconstruction of the MPFL requires operating at or near the medial epicondyle of the knee, early motion is indicated. During flexion and extension motion at the knee there is substantial movement of soft tissues around the medial epicondyle and therefore stiffness and loss of motion is common.\textsuperscript{58} Although some report a restriction of motion and weight bearing are required to protect against additional soft tissue injury following MPFL surgery,\textsuperscript{59,60} the authors of this manuscript suggest that immobilization is not worth the risk of post-operative stiffness. To decrease this risk of stiffness, range of motion is initiated progressively and early. Immediate range of motion as tolerated is allowed because the MPFL experiences maximal loads near full knee extension and during early knee flexion range of motion.\textsuperscript{28} As long as the graft is placed isometrically, increases in knee flexion range of motion should not place undue strain on the substitute tissue. Controlled mobilization reverses the effects of immobilization by stimulating collagen synthesis and optimizing alignment of healing tissues.\textsuperscript{61,62} This is of particular concern in ligaments as studies in animals have clearly shown that following even a few weeks of immobilization results in marked decreases in structural properties.\textsuperscript{63,64} These decreased properties occur due to subperiosteal bone resorption within the insertion sites as well as microstructural changes within the ligament substance. Remobilization was found to reverse the changes, however it took up to one year to return the properties to normal levels following only nine weeks of immobilization. A systematic review of eight papers of investigations following rehabilitation for MPFL reports that there is little differences in radiological or clinical outcomes between patients who were initially full weight bearing, began immediate active exercises, and were not immobilized in a knee brace, compared to those who were initially non-weight bearing, instructed not to exercise their knee, and were immobilized in a knee brace during the initial postoperative weeks.\textsuperscript{65}

Because post-surgical pain and swelling are known to inhibit quadriceps muscle control, both cryotherapy and electrical stimulation are used to alleviate pain by decreasing nerve conduction velocity and releasing endogenous opiates.\textsuperscript{66-70} In addition to these modalities the knee should be covered with a compression wrap of some form. The compressive dressing could be an ace wrap or “tube grip” type wrap to decrease existing swelling or prevent the onset of further swelling. The knee should also be kept in elevation early over the first 1-2 days following surgery.

Range of motion is initiated and progressed per surgeon’s protocol. The native intact MPFL has a load to failure rate of 208N.\textsuperscript{36,71,72} When the tibialis anterior is used as a graft substitute, its load to failure strength is 1553N,\textsuperscript{73} while a single strand of semitendinosus load to failure strength is 1060N.\textsuperscript{74} Due to the strength of substitute grafts, motion is provided to the knee and patellofemoral joint. After an assessment of passive patellar mobility, patellar mobilizations may be performed in all directions. Because knee motion stiffness and flexion contractures are one of the top complications following MPFL reconstruction,\textsuperscript{75} the patella can be mobilized if passive mobility is limited. This is in direct opposition to Cheatham and colleagues\textsuperscript{76} who report that only grade I and II superior and inferior glides are performed at the patellofemoral joint as they feel that medial and lateral glides may stress the surgical site. As long as fixation is appropriate concern regarding the stress of grade III and IV patellar mobilizations is not warranted. Patellar passive mobility of at least two quadrants in both the medial and lateral directions is desired. If there are less than two quadrants of passive mobility, joint mobilizations are instituted (Figure 10). As with most postoperative knee procedures the first post-operative priority is always gaining full extension to decrease the risk of developing a flexion contracture (Figure 11). Cyclops lesions, as seen with anterior cruciate ligament reconstructions, are not commonly reported following MPFL reconstruction, however capsular and or infrapatellar fat pad contracture, quadriceps inhibition, and poorly placed grafts can lead to motion complications.\textsuperscript{58}
The patient should ambulate weight bearing as tolerated progressing to full weight bearing for the first two weeks. Empirically, the authors have seen that typically the patient is full weight bearing within one week, however, it is not uncommon to reserve the second week for crutch use if needed or if pain and swelling persists for a longer amount of time.

Early exercises include quadriceps sets, heel slides, hamstring sets and gluteal sets until the patient is full weight bearing without symptoms. Because the hip and trunk are so important in maintaining proximal control for the knee and the patellofemoral joint, total leg strengthening (TLS) is initiated early. A phased approach is used to progressively strengthen the hip. The exercises used are based on electromyographic (EMG) studies demonstrating the hierarchy of maximal volitional contraction of the surrounding hip musculature. Bolgla and Boling performed a systematic review showing that both quadriceps and hip strengthening exercises are helpful to reduce pain in those with patellofemoral pain syndrome. They are also the mainstay during MPFL rehabilitation. Please see Table 1 for list of exercise in rank order based on percentage EMG activity.

If quadriceps inhibition occurs during this time frame, evidence has demonstrated neuromuscular electrical stimulation to be helpful in reducing strength loss after knee ligament surgery. Neuromuscular electrical stimulation should be performed with the athlete's volitional contraction in order to work optimally. Empirically, the authors of this manuscript have found that performing the quadriceps contractions in weight bearing increases contractile output better than when performed supine in long sitting.

Because of the replacement graft immediate strength, a brace or immobilizer is not used. Better understanding of graft mechanics and graft loading has resulted in advancement of rehabilitation. Basic exercises can begin including straight leg raises in all four planes, ankle isotonic strengthening in all planes, heel slides, quadriceps, hamstring and gluteal sets and eventually isotonic hamstring curls. Once full weight bearing is achieved without issues, closed kinetic chain exercises can begin. These include heel raises, mini-squats, progressive step-ups and downs, and balance and proprioception.

Clinical milestones for a safe progression at the end of phase I include full non-painful knee range of motion, full weight bearing without antalgia or limp, no increase in pain or swelling, at least 2 quadrants of patellar mobility, and ability to stand on a single leg.

**PHASE II: MODERATE PROTECTION PHASE (WEEKS 7-12)**

Goals for the moderate protection phase include: 1) maintaining full range of motion, 2) maintain repair,
3) gradual initiation of functional activities. During this phase most restrictions have been lifted.

Range of motion should be fairly well established at this time. If not, emphasis on motion should take precedence so as to not end up with an arthrofibrotic knee. Higher grade mobilizations and gentle overpressure to end ranges should be instituted to normalize the arthrokinematics of knee flexion and extension.

Exercises for strengthening in phase II can include a progression of squats by adding weight or adding proprioceptive component by squatting on balance board (Figure 12). Other closed chain exercises can include lunges starting on level ground and progressing to lunging to labile surface. Leg press exercises should be performed both bilaterally (Figure 13) and unilaterally to ensure adequate stimulus to the post-surgical knee. Lateral band walking places significant load on the hip musculature and is a great exercise to progress proximal hip dynamic stability and control (Figure 14).

Other hip exercises that are effective at strengthening at this time are single leg bridge (Figure 15) and hip hiking (Figure 16 A and B). Balance and proprioceptive exercises provide training for a stable base for the rest of the body to move from. The importance of balance and proprioception in athletics cannot be denied. An attempt to regain lost proprioception, regaining dynamic stability and neuromuscular control should be a priority. Neuromuscular training improves the nervous systems ability to generate optimal and fast muscle firing patterns, increases dynamic joint stability, and decreases joint reaction forces, which allows the muscles surrounding the joint to achieve a state of “readiness” to respond to joint forces and stimulus resulting in enhanced motor control. Early forms of balance training can begin in partial weight bearing progressing to full weight bearing. These can occur as weight shifting

| Table 1. Rank Order of Mean EMG during Exercises for Gluteus Medius and Gluteus Maximus Muscles |
|-----------------------------------------------|-------------------------------|---------------------------|
| Exercise                                      | Gluteus Medius | Exercise                      | Gluteus Maximus |
| Side-lying hip abduction                       | 81              | Single-limb squat              | 59              |
| Single-limb squat                              | 64              | Single-limb deadlift           | 59              |
| Lateral band walk                              | 61              | Transverse lunge               | 49              |
| Single-limb deadlift                          | 58              | Forward lunge                  | 44              |
| Sideways hop                                  | 57              | Sideways lunge                 | 41              |
| Transverse hop                                | 48              | Side-lying hip abduction       | 39              |
| Transverse lunge                              | 48              | Sideways hop                   | 39              |
| Forward hop                                   | 45              | Clam in 60 hip flexion         | 30              |
| Forward lunge                                 | 42              | Transverse hop                 | 35              |
| Clam in 30 hip flexion                        | 40              | Forward hop                    | 35              |
| Sideways lunge                                | 39              | Clam in 30 hip flexion         | 34              |
| Clam in 60 hip flexion                        | 38              | Lateral band walk              | 27              |

All values expressed as a % of MVIC.

Figure 12. Performance of squat exercise on a balance board providing not only lower extremity strengthening but also a proprioceptive and balance training effect.
in all directions. Squatting on a balance board or foam pad can help challenge balance and proprioception. Ultimately single-leg balance exercises can be done by applying a light perturbation or by using distractive elements such as throwing and catching a ball while balancing. In this manner perturbation training is done to induce dynamic knee stability allowing patients to develop their own compensation strategies to maintain stability.86

Single-leg exercises can begin including single-leg squats. These should be assessed critically as

Figure 13. Squatting on a leg press can increase the tolerable load in a controlled fashion.

Figure 14. Lateral band walking provides a method of incorporating additional strengthening effect to the hip abductors which are important proximal stabilizers to the leg and improves knee control.

Figure 15. Hip abductors are recruited highly with the lateral band walking drill.

Figure 16. A. Hip hike in the down position, B. Hip hike in the up position.
compensations can occur. These compensations generally result in increased hip adduction, internal rotation and tibial abduction. These can be seen subjectively when performing a single-leg squat with poor control (Figure 17A). At times this can be improved through strengthening exercises however visual and verbal cues may help improve poor postural control (Figure 17B). The clinical milestones for the moderate protection phase are to maintain previous milestones and to have full strength of hip, quadriceps and hamstrings. These milestones are important to be able to tolerate higher level activities in the minimum protection phase.

**PHASE III: MINIMUM PROTECTION PHASE (WEEKS 13-16)**

The minimum protection phase has the shortest time frame, which lasts from 13 to 16 weeks. The primary goals of this phase are to gradually return the athlete to functional activities.

To allow a gradual return to functional and athletic activities the involved knee has to have loads gradually applied up to that of the level needed to perform these higher functional activities such as running and jumping. This can be achieved by ensuring adequate strength through increased resistance and intensity during previous exercises such as squats, lunges, and leg press. Plyometric activities can begin with small bounding bilaterally such as double-leg jumping in place or double-leg jumping across multiple planes (Figure 18). Lateral and medial bounding can also be initiated which places specific stressors to the medial and lateral knee. Progressions of jumping/hopping should always start bilateral (jumping) and progressing to unilateral (hopping). Progressions to single-leg hopping are initiated in the next phase.

Clinical milestones to move into phase IV include all the prior milestones in addition to confidence in knee.

**PHASE IV: RETURN TO ACTIVITY (WEEKS 17-21 + )**

Goals for the return to activity phase include 1) progression of functional activities, 2) full return to all activities.

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**Figure 17.** A. Single-leg squat can be performed to examine more functional movement patterns of the entire lower extremity. A) The patient demonstrates poor frontal, transverse and sagittal control. B) improved control is assisted by visualization in front of mirror and verbal cues.

**Figure 18.** Bilateral jumping without pain or symptoms.
prior sports or recreational activities. In this goal the athlete is challenged at even higher levels of lower leg stressors that will determine if they are able to return to their prior sporting activities. This level may not be utilized for every patient. Not all patients that have MPFL reconstruction are higher-level athletes. If they do not desire or require this level of activity they would not be required to be rehabilitated to this level.

Once the athlete is comfortable with bilateral jumping they can attempt unilateral single-leg hopping on one foot. To start, it may be best to hop off of single affected side and landing on the unaffected side. Athletes following knee surgery are usually more able to hop from the surgical leg concentrically, but more concerned or afraid when asked to land eccentrically on the affected single-leg. Functional drills or activities such as sidestepping, ladder drills, or carioca can be done in a controlled manner to work on neuromuscular control. It is also at this last stage that the athlete can begin interval type programs such as return to running program.

DISCHARGE AND FULL RETURN TO COMPETITION
Discharge and full release and return to competitive sports is based on criteria that include: full range of motion, full strength and ability to achieve norms on standardized functional tests. The single leg step down test should be able to be performed with good form. This test is performed with the patient standing near the edge of a 20cm step. The patient is asked to place hands on hips and flex the test knee enough to touch the floor gently with opposite extremity. Five repetitions are scored by giving a single point for 1) using arms to maintain balance, 2) trunk lean either medial or lateral, 3) pelvis rotation or elevation, 4) tibial tubercle moving medial to 2nd toe, 5) unsteady unilateral stance; while two points are given for the tibial tubercle moving medial to the foot. A good score is needed to return to sports. A good quality score is 0-1 point, medium quality is 2-3 points, and poor quality is 4+ points. The step down test has been shown to have good interrater reliability and has the ability to differentiate those with moderate quality of movement (those with less hip abduction strength and decreased quadriceps flexibility) compared to those with good movement qualities.

Additionally, jumping and hopping tests are used. Criteria to be released for return to sports are for the athlete to be able to jump with both legs together horizontally 100% of height for males and 90% of height for females. Single-leg hop distances should be 90% of height for males and 80% of height for females. These are standardized norms for healthy non injured populations.

Nomura and colleagues followed 24 knees with after MPFL reconstruction for a mean follow-up of 11.9 years. Using the Crosby/Insall criteria and Kellgren/Lawrence grading systems and found that the association of knee osteoarthritis following MPFL reconstruction with or without a lateral release was small over the long-term. This is important as other surgical treatments such as proximal or distal realignments has been proven to be associated with osteoarthritis as early as 10 years following the procedure. Furthermore, Lippacher and colleagues found that of those who participated in sports prior to MPFL reconstruction, 100% returned to sports. Fifty-three percent returned to equal or higher levels, whereas 47% returned at lower levels. In those that returned to lower levels of athletics numerous reasons were cited including physical reasons such as decreased knee function and desire to avoid excessive sports after surgery, but also more psychological reasons too such as lack of time or interest and the fact that they were advised to be aware of the risks of high-pivot sports such as soccer.

PATIENT REPORTED OUTCOMES
Patient reported outcomes are instruments and rating scales used to measure outcomes from the patient's perspective. These outcomes may at times be very different from our clinical objective measures. These outcome tools examine many facets of knee health including swelling, giving way, pain and ability to function in activities of daily living. The authors of this manuscript recommend several following MPFL reconstruction. The Activities of Daily Living Scale and the Sports Activity Scale are both knee specific. The Sports Activity Scale have questions more related to higher levels of physical activity that are pertinent in active populations.
CONCLUSIONS
The science behind MPFL reconstruction and the ensuing rehabilitating continue to evolve as more evidence becomes available. The suggested protocol will help guide the patient to full recovery to sports and/or recreational activities without complications. An early emphasis on range of motion followed by a progression of strengthening exercises allows adequate incorporation of the soft tissue graft to the bony structures utilized during this reconstruction. Clinical milestones have been described to demonstrate when movement to the next phase is to be performed. MPFL reconstruction has been shown to have good results with low risk for major complications. As the surgery and the understanding of the MPFL continue to evolve so will the rehabilitation that follows. At present, clinicians must respect the soft healing tissue constraints but not at the expense of stiffness. Certainly higher levels of clinical research with longer follow up are needed to fully investigate the outcomes following this procedure.

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