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ERRATUM


Dr. Alexander Weber was incorrectly identified on this article as Alexander Weber, MD, and should have been listed as Alexander E. Weber, MD. This change does not affect any other aspect of this publication.

ABSTRACT

Background: The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments in the knee. With the prevalence of ACL tears increasing, there is a growing need for clinical tests to rule in and rule out a suspected tear. A new clinical test for detecting ACL tears has been introduced with preliminary studies showing promising results.

Hypothesis/Purpose: To systematically review and analyze information from the current literature on the diagnostic accuracy of the Lever Sign test for the use of diagnosing anterior cruciate ligament (ACL) injuries in a clinical setting.

Study Design: Systematic review and meta-analysis

Methods: A computerized search of PubMed, Cinahl, Scopus, and Proquest databases as well as a hand-search was completed on all available literature using keywords relating to the diagnostic accuracy of the Lever Sign Test. A quality assessment was performed on each article included in this review utilizing the Quality Assessment of Diagnostic Accuracy Studies (QUADAS).

Results: Eight articles were included, with only three studies exhibiting high quality, however the study samples were heterogenous. Included studies indicated that the Lever Sign test is both sensitive and specific in diagnosing ACL tears. Pooled sensitivity and specificity were 0.77 and 0.90, respectively. The negative likelihood ratio is 0.22 and the positive likelihood ratio is 6.60.

Conclusion: The Lever Sign test is comparable to other clinical tests used in current practice to detect an ACL rupture. The pooled data from current available literature on the Lever Sign indicate that a positive or negative test should result in a moderate shift in post-test probability. This test may be used in addition to other tests to rule in and rule out the presence of an ACL rupture.

Level of Evidence: 2a- Systematic Review of Level 2 diagnostic studies

Key Words: Anterior cruciate ligament, diagnostic accuracy, knee, Lelli test, Lever sign test, movement system
INTRODUCTION
Anterior cruciate ligament (ACL) tears are a common injury with a high prevalence occurring during athletic competitions.¹ The incidence of ACL tears among athletes has been reported at 68.6 per 100,000 persons per year.² A higher incidence of ACL tears has been noted in females compared to males when participating in the same sport.³ Anterior cruciate ligament injuries in athletes are more commonly due to non-contact mechanisms and are a result of deceleration and/or pivoting motions required in athletics.⁴ The ACL acts to resist posterior translation of the femur on the tibia, thus providing a large amount of stability to the knee joint.⁵ Early diagnosis is necessary to determine the best course of care and reduce the risk of further injury.

Clinical tests with favorable specificity and sensitivity are needed to determine if additional testing or imaging is warranted. Currently there are three diagnostic tests that are commonly used to assess for ACL tears including the Lachman’s test, anterior drawer test, and the pivot shift test. Of the tests previously stated, the Lachman test has long been reported to be the most sensitive and specific and should be included in every examination of a suspected ACL tear.⁶⁻⁷ Both the Lachman and pivot shift tests require the clinician to stabilize one segment of the leg while manipulating the other segment. This may prove challenging and produce inaccurate test results if the patient’s leg is of a larger girth or weight than the clinician is able to support. Therefore, a test that places the clinician in a biomechanical advantage may prove more practical.

Recently, a new clinical test for ACL was introduced called the Lever Sign test. The test is performed with the patient lying in supine and the examiner’s closed fist under the proximal third of calf. With the knee slightly flexed, the examiner’s opposite hand then applies a downward force just proximal to the knee joint. In an intact ACL, the heel should rise off the table, indicating a negative test. A disruption in the ACL will result in the patient’s heel remaining on the table, indicating a positive test.⁸ It has been found that at 30° of knee flexion, the greatest amount of anterior tibial translation occurs relative to the femur. By placing the fist under the calf, the knee is positioned in approximately 30° of flexion, placing the ACL origin and insertion at a maximal distance from each other. This orientation will maximally stress the ACL, explaining why an ACL deficient knee will not be able to overcome the posterior force directed at the femur.⁹

With the prevalence of ACL tears increasing, diagnostic tests with good utility are needed in order to assist the clinician in a diagnosis. At the time of submission, there were no previously published systematic reviews analyzing the diagnostic accuracy of the Lever Sign test. The purpose of this systematic review and meta-analysis is to determine the diagnostic accuracy of the Lever Sign test.

METHODS
Protocol and Registration
A systematic review protocol was registered with the International Prospective Register of Systematic Reviews – PROSPERO with registration number: CRD42018082534. This systematic review used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which is a 27-item checklist used to ensure optimal design and standardized reporting of systematic reviews and meta-analyses.¹⁰

Eligibility Criteria
The inclusion criteria set for this review included 1) studies that were completed on human subjects and 2) studies that evaluated the diagnostic accuracy of Lever Sign test for ACL rupture as compared to MRI or arthroscopic surgery, both of which are accepted reference standards. All peer-reviewed full-text articles of any study design were eligible for inclusion. Studies included subjects of any age and acuity of injury. Studies were excluded if the full text was not written in English.

Search Strategies
A comprehensive search was performed on PubMed, CINHAL, Scopus, and ProQuest in December 2017 and updated in April 2018 for articles relating to the diagnostic accuracy of the Lever Sign test. A search strategy was developed for PubMed utilizing variations of the keywords Lever Sign test, ACL rupture, and diagnostic accuracy, which can be found in Appendix 1. The search strategy was then
adapted for use in each specific database utilizing database-specific article indexing. The Walsh University library database was used to conduct a hand search for grey literature and other eligible articles in order to complete the comprehensive systematic search.

**Study Selection**

Titles and abstracts were retrieved from each database and duplicates were eliminated. Two review authors independently screened titles and abstracts found in the search with respect to the inclusion and exclusion criteria. The two review authors discussed discrepancies until consensus was achieved. Full text copies were then obtained for the remaining articles and were reviewed independently by two other authors for inclusion. Disagreements were discussed between the two full-text review authors and consensus was reached. Inter-rater reliability for title/abstract and full-text inclusion were calculated using Cohen's Kappa. The interpretation of the Cohen's unweighted kappa statistics used were: < 0 = poor, 0.01–0.20 = slight, 0.21–0.40 = fair, 0.41–0.60 = moderate, 0.61–0.80 = substantial, and 0.81–1 = almost perfect.

**Risk of Bias**

To identify the risk of bias in each individual article included in the review, the Quality Assessment of Diagnostic Accuracy Studies (QUADAS) tool was utilized and consists of 14 items that rate the overall quality of an article using the study's internal and external validity. The review authors gave a rating of “yes” (sufficiently covered) “no” (insufficiently covered) or “unclear” (insufficient detail included for open interpretation) for each item. The QUADAS tool has been reported to be reliable when assessing the strengths and weaknesses of diagnostic accuracy study. Articles that scored above a 10/14 were considered high quality and those below were considered low quality. While there is not an absolute qualification for high and low quality scores when using the QUADAS, these numbers are generally accepted in literature. Two review authors independently performed the quality assessment for each article and discrepancies were resolved by consensus. Inter-rater reliability for risk of bias was calculated using Cohen's Kappa.

**Data Extraction**

Two review authors extracted data independently from the included articles into a standardized form to ensure consistency of the data extraction process. The data were then substantiated by two review authors to ensure accuracy. Extracted information included: examiner skill level; patient age; patient gender; comparison standard; side of involvement; time since injury; study methodology; outcomes; diagnostic accuracy statistics including sensitivity and specificity. In the event that data components were not reported within the article, authors from included studies were contacted and a formal request was made for additional data. The definitions and calculations for diagnostic accuracy statistics can be found in Table 1.

**Statistical Analysis**

Pooling of results data for the quantitative synthesis was performed using Open Meta-analyst. Raw data from studies were input into a 2x2 table and Open Meta-analyst generated independent sensitivity and specificity values using the DerSimonian-Laird Random-Effects model. Cochran's Q and the I² statistic were assessed to determine the degree of heterogeneity. If I² was > 50%, a random effects model was used. The weighted average of pooled statistics was calculated and overall diagnostic accuracy values were determined. The diagnostic odds ratio (DOR) was calculated to determine the overall diagnostic power of the test. The I² statistic was used to determine variance across studies and indicate overall heterogeneity.

**Outcomes and Summary Measures**

Sensitivity represents the amount of true positives that the test was able to detect and specificity represents the amount of true negatives that the test was able to detect. Likelihood ratios (+/-) are used to determine the chance that an individual has the diagnosis after the test is performed. Further information regarding other statistical measures used can be found in Table 1.

**RESULTS**

**Study Selection**

The systematic electronic search of PubMed, CINHAL, Scopus, ProQuest, and a hand search resulted
in a total of 1,383 articles. After duplicates were removed the total yielded 1,305 articles. The title and abstracts of these articles were then screened and generated 18 full text articles to be screened ($\kappa=0.83;\ 95\%\ CI\ 0.67-0.98$). After full-text screening was completed ($\kappa=1.00;\ 95\%\ CI\ 1.00-1.00$), eight articles were found to meet the inclusion criteria.$^8,^{17-24}$ The summary of the literature search can be seen in Figure 1.

**Study Characteristics**

There were a total of 977 subjects between the eight included studies. Of these, 648 were males and 329 females. All of the studies were cohort design studies with subject sizes ranging from 33 to 400 and a mean of 122. The mean age range of patients included in the studies was 23 to 42 years old. Magnetic resonance imaging (MRI) was the reference standard used in two studies,$^8,^{22}$ arthroscopy was the reference standard for three studies$^19,^{21,24}$ and both were used in three of the studies.$^{18,20,23}$ Another study created an additional reference standard requiring at least two out of three findings consisting of 1) positive MRI, 2) excessive laxity of more than 3mm as measured on a KT-1000™ arthrometer (measures tibial translation), and 3) a positive findings on an independent examination that was performed at a later time.$^{20}$ All study characteristics are summarized in Table 2.

**Risk of Bias**

Five of the included studies$^8,^{18,20,21,23}$ were rated as low quality with a high risk of bias. The QUADAS ratings for each study can be found in Table 3. The most common item on QUADAS receiving a "No" or "Unclear" rating was Item 11. Studies in which this item was not met did not provide sufficient information regarding the individual’s involvement in the study who was interpreting the reference standard, therefore, it could not be determined if he/she had knowledge of the index test outcome. The Cohen’s unweighted kappa calculated for inter-rater reliability of the QUADAS assessment was 0.72, indicating substantial agreement (95% CI 0.58-0.86).

**Results of Individual Studies**

True negative, true positives, false negatives, and false positives for each of the studies can be found in Table 4. Sensitivity, specificity, positive and negative likelihood ratios, positive predictive values (PPV) and negative predictive values (NPV), and posttest probability values are presented in Table 5. All studies reported a sensitivity within the range of 0.37-1.00.$^8,^{18-24}$ Specificity was reported/calculated in five studies and was between 0.50-1.00.$^8,^{20-24}$ Positive and negative likelihood ratios were reported/calculated in five studies and were between 1.35-801.00 and 0-0.87, respectively.$^8,^{20-24}$ Positive predictive

### Table 1. Definitions and Calculations of Diagnostic Accuracy Statistics

<table>
<thead>
<tr>
<th>Statistical Measure</th>
<th>Definition</th>
<th>Calculation</th>
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<td>Sensitivity</td>
<td>Probability a positive test represents the population with the pathology</td>
<td>$\frac{TP}{(TP+FN)}$</td>
</tr>
<tr>
<td>Specificity</td>
<td>Probability that a negative test represents the population without the pathology</td>
<td>$\frac{TN}{(FP+TN)}$</td>
</tr>
<tr>
<td>Positive likelihood ratio</td>
<td>Ratio of population with the pathology and a positive test</td>
<td>$\frac{SN}{(1-SP)}$</td>
</tr>
<tr>
<td>Negative likelihood ratio</td>
<td>Ratio of population with the pathology and a negative test</td>
<td>$(1-SN)/SP$</td>
</tr>
<tr>
<td>Positive predictive value</td>
<td>Portion of population with the pathology and a positive test</td>
<td>$\frac{TP}{(TP+FP)}$</td>
</tr>
<tr>
<td>Negative predictive value</td>
<td>Portion of population without the pathology and a negative test</td>
<td>$\frac{TN}{(FN+TN)}$</td>
</tr>
<tr>
<td>Accuray</td>
<td>Proportion of the population who were correctly identified as having or not having the pathology</td>
<td>$\frac{(TP+TN)}{(TP+FP+FN+TN)}$</td>
</tr>
<tr>
<td>Interrater reliability</td>
<td>Ability of two or more examiners to repeat the test</td>
<td>$\frac{K=(P_t-P_0)}{(1-P_0)}$</td>
</tr>
<tr>
<td>Prevalence</td>
<td>Portion of the population that presently have the pathology</td>
<td>$\frac{TP+FP}{N} \times 100$</td>
</tr>
</tbody>
</table>

TP= True Positive, TN= True Negative, FP= False Positive, FN= False Negative, SN= Sensitivity, SP= Specificity, N= Total Number of Subjects, K= Cohen’s Kappa, PO= Observed Proportionate Agreement, PE= Probability of Random Agreement
values were reported/calculated in six studies and were between 0.47-1.00.\textsuperscript{8,19-24} In addition, NPV were reported/calculated in five of the studies and ranged between 0.57-1.00.\textsuperscript{8,20-24} Posttest probabilities for positive and negative tests were reported/calculated in five of the studies and ranged between 0.48-infinity and 0-0.43, respectively.\textsuperscript{8,20-24}

### Pooled Results

Results were compiled and run through Open Meta-Analyst software revealing a pooled sensitivity and specificity of 0.77 and 0.90 respectively, with a p-value of <0.01. Pooled data can be found in Figures 2-6. Heterogeneity across studies was high, therefore a random-effects model was used. Results of the meta-analysis indicated a high sensitivity (0.77) and high specificity (0.90) for the Lever Sign test. The negative likelihood ratio is 0.22 with a p-value <0.01 and the positive likelihood ratio is 6.60 with a p-value <0.01. The diagnostic odds ratio is 40.70 with a p-value of <0.01. Heterogeneity of the studies (\(I^2\)) was calculated for each statistic; sensitivity and specificity were reported as 89.64 and 74.16, negative and positive likelihood ratios were reported at 77.29 and 79.28, and heterogeneity for diagnostic odds ratios was 87.69. Meta-analysis results and forest plots for each statistic can be seen in Figures 2-6.

### DISCUSSION

The purpose of this systematic review and meta-analysis was to assess the diagnostic accuracy of the Lever Sign test. Based on the results of a systematic search of the literature, the Lever Sign has shown favorable diagnostic accuracy numbers in detecting ACL tears. The reported sensitivity and specificity for the Lever Sign was shown to be comparable to sensitivities and specificities for anterior drawer test, pivot shift test, and Lachman's test.\textsuperscript{7,25,26} The Clinical Practice Guidelines on Knee Stability and Movement Coordination Impairments: Knee Ligament Sprain Revision 2017 recommends the use of the pivot shift and Lachman's in every suspected
ACL tear. This recommendation along with other literature indicates that a thorough history and clinical examination by an experienced clinician may be just as accurate as an MRI in diagnosing ACL tears. The CPG reports sensitivity for the pivot shift test between 0.24-0.95, specificity between 0.95-0.98, positive likelihood ratio between 4.37-16.42, and negative likelihood ratio between 0.38-0.84. For Lachman’s, the sensitivity is reported between 0.85-0.95, specificity between 0.94-0.95, positive likelihood ratio between 1.39-40.81, and negative likelihood ratio of 0.22. A meta-analysis reported sensitivity and specificity of the anterior drawer test to be between 0.38-0.63 and 0.81-0.91, respectively. The positive likelihood ratio for anterior drawer was reported as 4.50 and the negative likelihood ratio reported as 0.22. A third clinical test with high specificity and sensitivity may be a valuable addition to the clinical examination to rule in as well as rule out ACL tears. A more useful tool in clinical practice may be likelihood ratios, which determine how accurate a test is in predicting a condition. Specificity and sensitivity only take into account two components of the contingency table, meaning that a diagnostic test could potentially have a large amount of false negatives while still having good specificity. Likelihood ratios take into consideration all aspects of the contingency table meaning that a large number of false negatives will largely impact the value. A pooled analysis reported sensitivity and specificity of 0.77 and 0.90 indicates that the Lever Sign test is good to rule in and rule out ACL tears, however likelihood ratios of 6.60 and 0.22 will only result in a moderate shift in the post-test probability.

Table 2. Study Characteristics.

<table>
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<tr>
<th>Author, Year</th>
<th>Sample Size</th>
<th>M</th>
<th>F</th>
<th>Study Design</th>
<th>Mean Age (Range)</th>
<th>Reference Standard</th>
<th>Exclusion Criteria</th>
<th>Inclusion Criteria</th>
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</thead>
<tbody>
<tr>
<td>Chong, 2017</td>
<td>33</td>
<td>21</td>
<td>12</td>
<td>Prospective Cohort Study w/o blinding</td>
<td>30.75 (11-62)</td>
<td>Arthroscopy</td>
<td>• past knee injury</td>
<td>• U/L knee injury (not sustained &lt;72 hours prior to exam) that resulted in symptomatic instability at 2 selected facilities</td>
</tr>
<tr>
<td>Devic, 2015</td>
<td>117</td>
<td>96</td>
<td>21</td>
<td>Cohort</td>
<td>25.8±5.9 (17-45)</td>
<td>MRI/Arthroscopy</td>
<td>• medial meniscus posterior root tear</td>
<td>• ACL tears determined by arthroscopic procedure</td>
</tr>
<tr>
<td>Jarbo, 2017</td>
<td>102</td>
<td>44</td>
<td>58</td>
<td>Cohort</td>
<td>23 (15-66)</td>
<td>MRI/Arthroscopy</td>
<td>• without MRI evaluation</td>
<td>• individuals w/CC of acute knee pain who were examined within 4 wks of their injury or onset</td>
</tr>
<tr>
<td>Lelli, 2014</td>
<td>400</td>
<td>281</td>
<td>119</td>
<td>Cohort</td>
<td>26.43±14.9</td>
<td>MRI</td>
<td>• cartilage defects</td>
<td>• definitive MRI diagnosis of U/L ACL rupture (partial or complete)</td>
</tr>
<tr>
<td>Lichtenberg, 2018</td>
<td>94</td>
<td>57</td>
<td>37</td>
<td>Cohort</td>
<td>34±15</td>
<td>Arthroscopy</td>
<td>• malignancies, systemic diseases, CNS disorders, complaints of knee locking, previous (partial) ruptures of the ACL</td>
<td>• minimum age of 16 years</td>
</tr>
<tr>
<td>Massey, 2017</td>
<td>91</td>
<td>61</td>
<td>30</td>
<td>Cohort</td>
<td>28±7 (16-60)</td>
<td>MRI</td>
<td>• past knee ligamentous reconstruction</td>
<td>• subjects presenting after a knee injury w/subjective swelling, an objective effusion, and uninjured, contralateral knee (no past injury or surgery)</td>
</tr>
<tr>
<td>Mulligan, 2017</td>
<td>60</td>
<td>38</td>
<td>22</td>
<td>Cohort</td>
<td>42±13.4 (18-65)</td>
<td>Arthroscopy or Positive finding in 2/3: • MRI</td>
<td>• possible fracture based on Ottawa knee rules</td>
<td>• subjects were between the ages of 18-65 w/complaint of knee pain rated as less than 7/10 on a verbal numerical rating scale</td>
</tr>
<tr>
<td>Thapa, 2015</td>
<td>80</td>
<td>50</td>
<td>30</td>
<td>Cohort</td>
<td>32.12 (21-42)</td>
<td>Arthroscopy</td>
<td>• none</td>
<td>• subjects possessing at least 20-120° ROM were eligible for inclusion</td>
</tr>
</tbody>
</table>

M=Number of Males, F=Number of Females, U/L=Unilateral, Wks=Weeks, W/+With, CC=Chief Complaint, CNS=Central Nervous System, ROM=Range of Motion, PCL=Posterior Cruciate Ligament
Preliminary research has shown similar sensitivity and specificity numbers for the Lever Sign test and mechanics of this test may allow for a more accurate result in situations where the patient’s limb is too heavy for the clinician to support. All studies included in this review had more male subjects than female subjects, which may influence the clinical application of the test due to ACL tears being...
Table 5. *Summary of Results.*

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>SN</th>
<th>SP</th>
<th>LR+</th>
<th>LR−</th>
<th>PPV</th>
<th>NPV</th>
<th>PP</th>
<th>PP+</th>
<th>PP−</th>
<th>DOR</th>
<th>Overall Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chong19, 2017</td>
<td>.88*</td>
<td>UTD</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.97**</td>
<td>UTD</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.82†</td>
<td>UTD</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00‡</td>
<td>UTD</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Deveci18, 2015</td>
<td>.94‡</td>
<td>UTD</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>UTD</td>
<td>UTD</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Jarbo23, 2017</td>
<td>.63</td>
<td>.90</td>
<td>6.4</td>
<td>0.41</td>
<td>87%</td>
<td>71%</td>
<td>50%</td>
<td>86.49%</td>
<td>29.23%</td>
<td>15.49</td>
<td>76.47%</td>
</tr>
<tr>
<td>Lelli14, 2014</td>
<td>1</td>
<td>1</td>
<td>∞</td>
<td>∞</td>
<td>100%</td>
<td>100%</td>
<td>50%</td>
<td>0%</td>
<td>641.60</td>
<td>1.00</td>
<td>100%</td>
</tr>
<tr>
<td>Lichtenberg24, 2018</td>
<td>.39</td>
<td>1</td>
<td>36.9</td>
<td>.61</td>
<td>100%</td>
<td>∞</td>
<td>64.79%</td>
<td>∞</td>
<td>35.21%</td>
<td>60.18</td>
<td>71.26%</td>
</tr>
<tr>
<td>Massey22, 2017</td>
<td>.83</td>
<td>.8</td>
<td>4.15</td>
<td>0.21</td>
<td>94%</td>
<td>57%</td>
<td>78.02%</td>
<td>93.65%</td>
<td>42.86%</td>
<td>19.67</td>
<td>82.42%</td>
</tr>
<tr>
<td>Mulligan25, 2017</td>
<td>.38</td>
<td>.72</td>
<td>1.35</td>
<td>0.87</td>
<td>47%</td>
<td>63%</td>
<td>40%</td>
<td>48%</td>
<td>36%</td>
<td>1.56</td>
<td>58%</td>
</tr>
<tr>
<td>Thapa21, 2015</td>
<td>.86</td>
<td>.91</td>
<td>7.71</td>
<td>0.16</td>
<td>85.71%</td>
<td>88.89%</td>
<td>43.75%</td>
<td>85.71%</td>
<td>11.11%</td>
<td>48.00</td>
<td>87.50%</td>
</tr>
</tbody>
</table>


**=Orthopedic Surgeon, †= Orthopedic Physician Assistant, ‡= Under Anesthesia, §= Pre-anesthesia, ||= Anesthesia

Figure 2. *Forest Plot of Sensitivity.* Abbreviations: C.I. = confidence interval; TP = true positive, FN = false negative.

Figure 3. *Forest Plot of Specificity.* Abbreviations: C.I. = confidence interval; TN = true negative, FP = false positive.
more prevalent in females.\(^4\) Leg girth differences between males and females may impact sensitivity and specificity due to males tending to have a larger and heavier leg than females. A heavier leg will require more force to be placed through the distal thigh during the test, and results may be inaccurate if this force is not enough to overcome limb resistance. Certain studies excluded subjects if any concomitant tears were suspected or known or if they had a previous ACL tear on the same limb. Meniscal
and medial collateral ligament (MCL) tears commonly accompany an ACL tear. It is also not uncommon for an athlete to re-tear a reconstructed ACL. In addition, pain, swelling, and muscle guarding are common in patients with acute ACL tears and also were not adequately addressed in the research. Conducting the Lever Sign test on these patients may yield different sensitivity and specificity numbers.

There were several limitations noted in the included studies. Limited studies were available for inclusion and sample sizes varied from small to large. Methodological procedures that predisposed studies to bias were inclusion criteria of confirmed ACL tears, comparing results of uninjured contralateral leg, unclear blinding of examiners, and missing 2x2 tables. The study with the largest sample size only included patients who were confirmed to have an ACL tear via MRI. The contralateral uninjured leg was assessed using the Lever Sign test and included the results in their 2x2 table. No false negatives or false positives were reported, resulting in a sensitivity and specificity of 1.00. However, this study was not the only one to include patients with a confirmed ACL tear and compare the contralateral uninjured leg. Within studies, there was a lack of false positives found, but it is unclear if this is due to participants with false positives being removed from the study. Authors from three studies were contacted for missing data, however only data from two of the authors was obtained. Without the data from the third author, specificity was unable to be calculated and therefore not included in the meta-analysis. Bias was noted within the studies with inadequate descriptions of the examiners performing the test. Exclusion criteria introduced additional limitations within the studies such as excluding patients with concomitant tears or a previous ACL tear on the leg to be tested.

The Lever Sign test is relatively new, therefore, there is limited research on the topic. Strong exclusion criteria were unable to be developed in this systematic review due to the limited number of studies on the topic. Studies were only excluded if they were not written in English, which limits the ability to control the quality of the included studies. Without strong exclusion criteria, study quality was a major limitation. The inclusion criteria developed for this systematic review lead to high Cohen’s kappa scores, with title and abstract screening showing substantial agreement and the full text screening showing almost perfect agreement. While the QUADAS test has been shown to have low interrater reliability in the literature, the kappa score for this systematic review showed substantial interrater agreement.

It is recommended that further research be completed on the diagnostic accuracy of the Lever Sign test. Studies should include a larger number of female participants in order to better represent the overall population of ACL tears. Future research should be completed examining the effect of examiner’s hand size on the accuracy of the test. Differences in hand size may place the leg in varying positions, not always maintaining 30° of knee flexion. In this instance, the ACL is not at maximum tension which may yield inconsistent results between examiners. Partial, full thickness, and concomitant tears, as well as acuity, pain, and swelling may also play a role in the accuracy of the Lever Sign test and are parameters that should be included in future studies. It is also recommended that more studies be conducted that do not include the patient being tested under anesthesia in order to improve the clinical applicability of this test. There is currently not enough data to determine any differences in likelihood ratios or sensitivity/specificity when testing under anesthesia vs testing in the awake patient. Tests that can be used to both rule in and rule out pathologies are ideal in clinical practice and research indicates that the Lever Sign test is both specific and sensitive, however quality evidence is currently lacking. Recommendations to reduce bias in future research should be aimed to include larger sample sizes, increased external and internal validity, inclusion of patients with an unknown ACL status, and blinding of examiners to both reference standard and index test results.

CONCLUSIONS

There are a variety of different clinical tests that can be useful in diagnosing ACL rupture. Clinicians utilize clinical tests with a high sensitivity to rule out a diagnosis following a negative test, and specificity to rule in a diagnosis following a positive test. While there is still no single clinical test that is consistently accurate, the results of this study indicate that the Lever Sign test, when used with other tests, may
help provide the clinician with a more complete clinical picture about the status of the ACL.

REFERENCES
APPENDIX 1. DETAILS OF PUBMED SEARCH STRATEGY

1 reproducibility of results [Mesh Term]
2 reproducibility of results [Text Term]
3 sensitivity and specificity [Mesh Term]
4 sensitivity and specificity [Text Term]
5 diagnostic accuracy [Text Term]
6 interrater reliability [Text Term]
7 intrarater reliability [Text Term]
8 validity [Text Term]
9 result reproducibility [Text Term]
10 sensitivity [Text Term]
11 specificity [Text Term]
12 1 OR 2 OR 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9 OR 10 OR 11
13 physical examination [Mesh Term]
14 diagnostic techniques and procedures [Mesh Term]
15 diagnosis, differential [Mesh Term]
16 diagnostic test approval [Mesh Term]
17 physical examination [Text Term]
18 diagnostic techniques and procedures [Text Term]
19 diagnosis, differential [Text Term]
20 diagnostic test approval [Text Term]
21 lever sign test [Text Term]
22 lelli test [Text Term]
23 lelli's test [Text Term]
24 diagnostic techniques [Text Term]
25 diagnostic procedure [Text Term]
26 13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19 OR 20 OR 21 OR 22 OR 23 OR 24 OR 25 OR 26
27 anterior cruciate ligament injuries [Mesh Term]
28 anterior cruciate ligament injuries [Text Term]
29 anterior cruciate ligament/injuries [Mesh Term]
30 anterior cruciate ligament/injuries [Text Term]
31 anterior cruciate ligament [Mesh Term]
32 anterior cruciate ligament [Text Term]
33 full ACL tear [Text Term]
34 partial ACL tear [Text Term]
35 acute ACL injury [Text Term]
36 chronic ACL injury [Text Term]
37 ACL Rupture [Text Term]
38 27 OR 28 OR 29 OR 30 OR 31 OR 32 OR 33 OR 34 OR 35 OR 36 OR 37
39 12 AND 36 AND 38
ABSTRACT

Background: Hip extension is an important action in daily activities (standing, stepping and walking) and sporting actions (running, sprint-running and jumping). Though several different exercises exist, a comprehensive understanding of which exercises best target the gluteus maximus (Gmax) and the magnitude of muscular excitation associated with each exercise is yet to be established.

Purpose: The purpose of this systematic review was to describe the electromyographic (EMG) excitation of the Gmax during body weight exercises that utilize hip extension.

Methods: A systematic approach was used to search Pubmed, Sports Discuss, Web of Science and Science Direct using the Boolean phrases (gluteal OR gluteus maximus) AND (activity OR excitation OR activation) AND (electromyography OR EMG) AND (hip extension). Articles that examined injury-free participants of any age, gender or excitation level were included. Articles were excluded when not available in English, where studies did not normalize EMG excitation to maximum voluntary isometric contraction (MVIC), where a load or resistance was added to the exercise, or where no hip extension occurred. Exercises were grouped into vertical and horizontal (anteroposterior or posteroanterior) force vectors.

Results: Thirty-nine studies of high methodological quality were retained for analysis. Twenty-five exercises were performed in the vertical vector (average: 33.4% MVIC, highest: single leg wall squat 86% MVIC), fourteen exercises were performed in the horizontal (anteroposterior) force vector (average: 32.8% MVIC, highest: single leg bridge 54.2% MVIC), while thirty-eight exercises were included in the horizontal (posteroanterior) vector (average: 30.4% MVIC, highest: plank with bent leg hip extension 106.2% MVIC).

Limitations: The differences in subject's backgrounds, exercise technique and the methodological approaches varied between studies, most notably in the different positions used for obtaining MVIC, which could have dramatically impacted normalized levels of gluteal activation.

Conclusion: The findings from this review provide an indication of Gmax muscle excitation generated by a variety of hip extension body weight exercises, which may assist practitioners in making exercise selection decisions for programming.

Keywords: gluteal musculature, hip strengthening, force vector, EMG, movement system
INTRODUCTION

Hip extension is an important joint action in daily activities (standing, stepping and walking) and sporting actions (running, sprint-running and jumping). The hip extensor musculature are capable of producing the highest torque compared to any other muscle group involved in hip movement. Hip extension primarily involves the gluteus maximus (Gmax), hamstrings (long head of biceps femoris, semimembranosus, and semitendinosus), and posterior head of the adductor magnus. Recruitment of the Gmax and associated hip extensor muscles, coupled with efficient movement are required for optimal hip extension force production. Although several muscles contribute to hip extension, the focus for this article is on the Gmax musculature and its role in hip extension during body weight exercise.

Though several different exercise protocols exist, scientific evaluation of their specific effects on the Gmax has yet to establish which exercises best isolate the musculature and what level of muscular excitation is elicited. Electromyography (EMG) is a tool that provides insight into how the neuromuscular system behaves via amplitude information regarding the timing characteristics and muscle excitation levels for a given recording condition. Historically, exercises have been examined through EMG analysis with the general consensus assumed that exercises producing higher levels of muscular excitation are associated with greater long-term strength and size increases. Though debate remains about the application of EMG in a practical context it is a commonly implemented method within the literature and therefore may be used as a guideline to assist in understanding musculature excitation.

Weakness and imbalanced strength in the Gmax is associated with multiple lower extremity injuries and lower back pain which can necessitate substitution by synergist musculature. Consequently, practitioners often choose to incorporate Gmax targeted exercise in both rehabilitation and sport settings by starting with unloaded (i.e. body weight only) exercises. An extensive variety of body weight hip extension exercises are used for training, both in athletic performance and in rehabilitation programming. As one alters the body’s position during the different hip extension exercise options, this will result in a change in the amount of body mass being moved by the hip musculature and the orientation of the gravitational force-vector. Selecting exercises by taking into regard the direction of the force-vector (i.e. horizontal vs vertical, Figure 1) may play an important role in developing different and specific functional adaptations. Moreover, specificity of movement promotes intermuscular coordination which has been shown to increase transference to sport performance. Therefore, classifying hip extension body weight exercises by the respective force vectors may be important for best exercise selection for activity type and conversion into performance outcomes.

It is important to take into consideration the force-vector associated with different exercises when developing programming for rehabilitation or performance enhancement as different force-vector exercises have been shown to elicit differences in Gmax EMG amplitudes. This was certainly the case in loaded hip extension exercises with equated 10 repetition maximum loads that resulted in a significant greater amount of mean lower and upper Gmax excitation found in the horizontal vector exercise (barbell hip thrust, 40.8-69.5% MVIC) compared to the vertical vector exercise (barbell back squat 14.9-29.4% MVIC). Similarly, Gmax excitation was 16% higher during the barbell hip thrust (horizontal).
compared to the hex bar deadlift (vertical) with 1RM loading. Whether these differences occur in unloaded hip extension exercises is unknown. Therefore, the purpose and focus of this systematic review was to describe the EMG excitation of the Gmax during body weight exercises that utilize hip extension. Exercises were grouped by force vector position to assist practitioners in making decisions for exercise selection that targets Gmax excitation.

METHODS

Literature Search Strategies
The review was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) statement guidelines. A systematic search of the research literature was undertaken for studies that investigated EMG amplitude (given as mean %MVIC) for the Gmax in body weight exercises that utilised dynamic hip extension. Studies were found by searching Pubmed, Sports Discuss, Web of Science and Science Direct electronic databases from inception to November 1st 2017 using the following Boolean search phrases: (gluteal OR gluteus maximus) AND (activity OR activation) AND (electromyography OR EMG) AND (hip extension). Additional studies were also found by reviewing the reference lists from retrieved studies.

Inclusion and Exclusion Criteria
Articles that examined injury-free participants of any age, sex or activity level were included. No restrictions were imposed on publication date or publication status. Studies were limited to English language. Studies were excluded that did not normalize EMG excitation to %MVIC or did not present the results as numbers (i.e. results presented as figures). This review focussed on exercises performed without any additional load, therefore only body weight exercises were included and studies which contained an external load (e.g. barbell, dumbbell, band, and machine) were excluded. Plyometric or hopping movements were also excluded as they are performed with higher acceleration, therefore they have an advantage in terms of eliciting high levels of gluteal excitation. Moreover, plyometric exercises are higher end performance type exercises and should be used once an individual exhibits prerequisite strength levels (eccentric) which includes mobility and stability.

Study Selection
One reviewer (PM) searched the databases and selected studies. A second reviewer (EF) was available to assist with study eligibility. No disagreements about the appropriateness of an article were encountered. A search of electronic databases and a scan of article reference lists revealed 355 relevant studies, with an additional 14 studies found via hand searches of references lists (Figure 2). After removing duplicate studies (n = 68), screening titles (n = 78) and abstracts (n = 149), 49 studies were retained. Following full-text screening, a further 10 studies were excluded (6 studies were not normalised to MVIC, 4 studies reported results as figures), thereby, 39 studies were retained for this review.

Methodological Quality Score
Methodological quality was assessed using the quality index of Downs and Black modified version. A value of 0 or 1 was assigned to the different subcategories of the following items: reporting, external validity, and internal validity. A total score < 10/17 was considered to be low quality, while scores ≥ 10/17 were presumed to be high quality.

RESULTS
Quality assessment scores of the thirty-nine articles included ranged from 10 to 14, with an average score of 11.6 out of 17, indicating a high methodological quality for the studies reviewed (Appendix 1). There were a total number of 938 subjects who performed 77 total exercise variations. Appendix 1 summarises all studies included. All studies used surface electrodes, with the exception of Selkowitz, Beneck, Powers who used fine wire electrodes. Two studies reported the superior (upper) and inferior (lower) regions of the Gmax, while the remaining Gmax values were obtained from electrodes positioned on muscle belly (descriptions of electrode placement are given in Appendix 1). Results are presented within vertical and horizontal force vector tables with horizontal exercises further sub-divided into anteroposterior and posteroanterior due to high number of exercises within each sub-division). Results for the same exercise have been averaged from the combined totals to present a mean percentage of MVIC and mean range value for the exercise. However, due to differences between study methodologies
caution should be used for interpreting the findings, therefore, the mean values should be interpreted as a guideline. Exercises were grouped by the magnitude of mean Gmax excitation and stratified into the four levels of activity: 0-20% MVIC was considered low muscle excitation, 21-40% MVIC was considered moderate muscle excitation, 41-60% MVIC was considered high muscle excitation, and greater than 60% MVIC was considered very high muscle excitation. This classification scheme provides a means by which the practitioner can select exercises, that match the capabilities of their client/athlete thus targeting neuromuscular, endurance, or strength type training, and provides a means by which the Gmax can be progressively overloaded in a systematic fashion. Table 4 provides a summary of average %MVIC for Gmax in the different force vector positions.

**Vertical force vector**
The Gmax excitation for exercises performed in the vertical force vector can be found in Table 1. Twenty-five different exercises were performed in this force vector with the most common exercises being the single leg squat (9), lunge (7), and lateral step up (6). The highest mean excitation was found in the single leg wall squat with other leg knee extended (86 ± 43% MVIC) and the lowest activity occurred in the squat with 0° trunk flexion (6.1 ± 4.0% MVIC). Eight exercises were classified as low excitation, ten were moderate excitation, four were high excitation, and three were very high excitation. Of note, variations of the deadlift exercises were included in this force vector although the force vector is not truly vertical and crosses with the anteroposterior force vector.

**Horizontal force vector (Anteroposterior)**
Information regarding the Gmax excitation for the anteroposterior force vector can be observed in Table 2. Fourteen different exercises were performed in this force vector with the most common exercises being the single leg bridge (6) and two-legged bridge (6). The highest absolute excitation was found in the...
single leg bridge (54.2% MVIC), though when this exercise was averaged from six studies the mean activity was 39.9% MVIC. The lowest excitation occurred in the bridge with feet on a gymnastics ball exercise (13.0% MVIC). Four exercises were classed as low excitation, five were moderate excitation and five were high excitation.

Horizontal force vector (Posteroanterior)

Information regarding the Gmax excitation for the posteroanterior force vector can be found in Table 3. Thirty-eight different exercises were performed in this force vector. The highest mean excitation was found in the plank with bent leg hip extension (106.2% MVIC) followed by prone hip extension with upper body on

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**Table 1.** Comparison of muscle excitation in the Gluteus Maximus for all vertical force vector exercises. Values given as the mean and the standard deviation.

<table>
<thead>
<tr>
<th>Classification level of %MVIC</th>
<th>Exercise</th>
<th>Number of studies</th>
<th>Number of subjects</th>
<th>Mean %MVIC of Gmax</th>
<th>Range % MVIC of Gmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>Squat with 0° trunk flexion³⁸</td>
<td>1</td>
<td>20</td>
<td>6.1 ± 4.0</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Squat with 15° trunk flexion³⁶</td>
<td>1</td>
<td>20</td>
<td>6.3 ± 4.0</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Squat with 30° trunk flexion³⁴</td>
<td>1</td>
<td>20</td>
<td>8.0 ± 4.9</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Lunge with pelvic compression belt³⁸</td>
<td>2</td>
<td>26</td>
<td>13.9 ± 7.7</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Squat²⁸,³⁵</td>
<td>3</td>
<td>58</td>
<td>14.4 ± 4.3</td>
<td>10.5-21.7</td>
</tr>
<tr>
<td></td>
<td>Forward step up and over²⁹</td>
<td>1</td>
<td>44</td>
<td>16.5 ± 11.7</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Lateral step down³⁸</td>
<td>1</td>
<td>34</td>
<td>16.5</td>
<td>8.4-24.6</td>
</tr>
<tr>
<td></td>
<td>Lunge with trunk extension³⁵</td>
<td>1</td>
<td>10</td>
<td>19.3 ± 11.8</td>
<td>Not available</td>
</tr>
<tr>
<td>21-40%</td>
<td>Lunge with trunk flexion³¹</td>
<td>1</td>
<td>10</td>
<td>22.3 ± 12.0</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Lunge³¹,³², ³³, ³⁴, ³⁶, ³⁷, ³⁸</td>
<td>7</td>
<td>185</td>
<td>22.8 ± 12.3</td>
<td>11.4-44</td>
</tr>
<tr>
<td></td>
<td>Forward step down³⁹</td>
<td>1</td>
<td>34</td>
<td>23.1</td>
<td>19.0-27.2</td>
</tr>
<tr>
<td></td>
<td>Lateral lunge²⁴,⁴⁰</td>
<td>2</td>
<td>61</td>
<td>26.5 ± 14.5</td>
<td>12.4-41</td>
</tr>
<tr>
<td></td>
<td>Single leg wall squat, other leg knee flexed³⁸</td>
<td>1</td>
<td>34</td>
<td>26.8</td>
<td>21.6-32.0</td>
</tr>
<tr>
<td></td>
<td>Single leg mini squat, other leg knee flexed³⁴,³⁶</td>
<td>2</td>
<td>57</td>
<td>34.6 ± 16.3</td>
<td>20.3-57</td>
</tr>
<tr>
<td></td>
<td>Single leg squat with pelvic compression belt³⁶</td>
<td>1</td>
<td>20</td>
<td>35.5 ± 21.7</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Lateral step up²³, ²⁴, ²⁵, ²⁶, ²⁷, ²⁸, ²⁹</td>
<td>6</td>
<td>143</td>
<td>36.0 ± 17.8</td>
<td>16-63.8</td>
</tr>
<tr>
<td></td>
<td>Single leg deadlift with pelvic compression belt³²</td>
<td>1</td>
<td>20</td>
<td>36.5 ± 21.9</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Forward step up³⁶, ³⁷, ³⁸, ³⁹, ⁴⁰, ⁴¹</td>
<td>6</td>
<td>119</td>
<td>38.7 ± 19.5</td>
<td>15.7-74</td>
</tr>
<tr>
<td>41-60%</td>
<td>Single leg squat³¹, ³², ³³, ³⁴, ³⁵, ³⁶, ³⁷, ³⁸, ³⁹</td>
<td>9</td>
<td>227</td>
<td>43.2 ± 14.9</td>
<td>18.9-81.2</td>
</tr>
<tr>
<td></td>
<td>Single leg deadlift³⁷, ³⁸, ³⁹</td>
<td>3</td>
<td>65</td>
<td>48.6 ± 14.6</td>
<td>27.9-59</td>
</tr>
<tr>
<td></td>
<td>Transverse lunge³¹</td>
<td>1</td>
<td>21</td>
<td>49 ± 20</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Retro step up³⁵</td>
<td>1</td>
<td>23</td>
<td>59 ± 35</td>
<td>Not available</td>
</tr>
<tr>
<td>&gt;60%</td>
<td>Skater squat³²</td>
<td>1</td>
<td>24</td>
<td>66.2</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg squat with rotation³⁶</td>
<td>1</td>
<td>9</td>
<td>78 ± 45</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg wall squat, other leg knee extended³⁶</td>
<td>1</td>
<td>23</td>
<td>86 ± 43</td>
<td>Not available</td>
</tr>
</tbody>
</table>

Gmax = Gluteus Maximus  MVIC = maximum voluntary isometric contraction

---

**Table 2.** Comparison of muscle excitation in the Gluteus Maximus for all anteroposterior force vector exercises. Values given as the mean and the standard deviation.

<table>
<thead>
<tr>
<th>Classification level of %MVIC</th>
<th>Exercise</th>
<th>Number of studies</th>
<th>Number of subjects</th>
<th>Mean %MVIC of Gmax</th>
<th>Range % MVIC of Gmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>Bridge with feet on a swing ball and hamstring curl³⁶</td>
<td>1</td>
<td>26</td>
<td>10.9</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Bridge with feet on a swing ball³⁶</td>
<td>1</td>
<td>26</td>
<td>13.0</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Bridge with hamstring curl³⁶</td>
<td>1</td>
<td>26</td>
<td>18.5</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Bridge with knees extended and feet on a swing ball³⁶</td>
<td>1</td>
<td>59</td>
<td>20 ± 14</td>
<td>Not available</td>
</tr>
<tr>
<td>21-40%</td>
<td>Bridge³⁶</td>
<td>6</td>
<td>177</td>
<td>23.3 ± 8.8</td>
<td>16.4-41.5</td>
</tr>
<tr>
<td></td>
<td>Single leg bridge with foot on board³⁶</td>
<td>1</td>
<td>26</td>
<td>28.4</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Bridge with verbal and tactile cues³⁹</td>
<td>1</td>
<td>15</td>
<td>33.0</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Supine manual resisted hip extension²</td>
<td>1</td>
<td>26</td>
<td>34.7</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg bridge³¹, ³², ³³, ³⁶, ³⁷, ³⁸, ³⁹</td>
<td>6</td>
<td>153</td>
<td>39.9 ± 7.6</td>
<td>32.6-54.2</td>
</tr>
<tr>
<td>41-60%</td>
<td>Single leg bridge. DOM leg 135° knee flexion with dorsiflexed ankle. Non-DOM leg knee relaxed in flexion and femur vertical¹⁰</td>
<td>1</td>
<td>28</td>
<td>40.4 ± 24.6</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg bridge. DOM leg 90° knee flexion with foot flat. Non-DOM leg knee relaxed in flexion and femur vertical¹⁰</td>
<td>1</td>
<td>28</td>
<td>47.2 ± 28.1</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg bridge. DOM leg 135° knee flexion with foot flat. Non-DOM leg knee extended¹⁰</td>
<td>1</td>
<td>28</td>
<td>47.4 ± 24.8</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg bridge. DOM leg 90° knee flexion with dorsiflexed ankle. Non-DOM leg knee relaxed in flexion and femur vertical¹⁰</td>
<td>1</td>
<td>28</td>
<td>49.1 ± 26.4</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Single leg bridge. DOM leg 90° knee flexion with foot flat. Non-DOM leg knee extended¹⁰</td>
<td>1</td>
<td>28</td>
<td>51.0 ± 28.1</td>
<td>Not available</td>
</tr>
</tbody>
</table>

DOM = dominant  Gmax = Gluteus Maximus  MVIC = maximum voluntary isometric contraction
The lowest excitation occurred in the prone hip extension from hip flexion of 30° (9.7 ± 2.9% MVIC). Seven exercises were classed as low excitation, twenty-two were moderate excitation, seven were high excitation, and two were very high excitation.

**Summary of force vectors**
Details of Gmax excitation for all positions are summarized in Table 4. The vertical position produced the highest average excitation (33.4% MVIC) followed by the anteroposterior (32.8% MVIC) and posteroanterior (31.5% MVIC). A limitation of positional grouping by force vector is that similar average excitation levels were found between vectors due to a wide variation in the different exercises. The posteroanterior force vector had the absolute highest excitation value (106.2% MVIC) for the plank with bent leg hip extension exercise while the vertical vector had the lowest excitation value
DISCUSSION
The purpose of this systematic review was to quantify the EMG excitation of the Gmax musculature during body weight hip extension exercises. Findings from the thirty-nine studies reviewed showed that the level of Gmax EMG excitation ranged from 6.1% to 106.2% MVIC. The wide range of Gmax EMG found from hip extension exercises in this review is comparable to the levels (4% to 103% MVIC) found in Gmax excitation during hip abduction and external rotation exercises reported by Macadam, Cronin, Contreras.23 Pooled results from in the three force vectors show a similar average level of EMG excitation between vectors: vertical (33.4%), anteroposterior (32.8%) and posteroanterior (30.5%). However, when looking at the range of EMG excitation it would seem that levels can be affected by changes in body position, which changes the direction in which force is applied to in relation to the body and the complexity of the exercise.

Vertical force vector
Twenty-five exercises were performed in the vertical vector (average: 33.4% MVIC, highest mean: single leg wall squat 86.0% MVIC). Unilateral versions of a vertical oriented exercise resulted in greater Gmax excitation than the bilateral version. This can be seen from all versions of the squat which resulted in small EMG excitation levels, compared to the single leg squat which resulted in levels of moderate, high and very high during differing versions. The single leg squat was the most used exercise (9 studies) in this vector and though its average excitation level was high (47.8% MVIC), it was found to elicit a wide range of excitation (18.9-81.2% MVIC). Reasons for range of values may relate to the depth of the squat, subject's proficiency and experience of the exercise, and the position of the free leg. This is highlighted by Ayotte, Stetts, Keenan, et al.24 who found the highest level of EMG excitation in the single leg squat when the free leg is extended from the knee (86% MVIC). While when the free leg is flexed from the knee and behind the body, i.e. the skater squat version, the level of excitation was 66.2% MVIC.25 The single leg squat exercise was also found to result in excitation level differences between genders, with females exhibiting greater levels than males in three studies.26-28 Females were also found to exhibit greater excitation levels in single leg wall slide, lateral step down and forward step down exercises.28 Reasons for differences may relate to structural differences (females having an increased pelvic width to femoral length ratio) or differences in hip abductor strength requiring greater Gmax excitation to control the pelvis in the unilateral exercises.28 All three studies assessed exercises in the vertical vector, therefore due to the greater stability requirements in this vector it is unknown if these gender differences occur in other force vectors.

A commonly used vertical exercise was the lunge (7 studies) which resulted in a small to moderate level of excitation (11-44% MVIC), thus may be suitable as an early progressive exercise from bilateral exercises due to its split-stance two point of contact providing a base of stability that challenges balance from the wide foot base. Once mastered, progression can include forward and lateral step down exercises which elicited small excitation in males and

### Table 4. Summary of average %MVIC for Gluteus Maximus in different force vector positions.

<table>
<thead>
<tr>
<th>Force vector position</th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Anteroposterior</td>
</tr>
<tr>
<td>Number of studies</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>Number of subjects</td>
<td>534</td>
<td>255</td>
</tr>
<tr>
<td>Number of exercises</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>Gmax average %MVIC</td>
<td>33.4</td>
<td>32.8</td>
</tr>
<tr>
<td>Gmax range %MVIC</td>
<td>6.1-86.0</td>
<td>10.9-54.2</td>
</tr>
</tbody>
</table>

Gmax = Gluteus Maximus, MVIC = maximum voluntary isometric
moderate excitation in females. While subsequent progressive exercises can include the forward and lateral step up exercises which resulted in moderate to high excitation levels. Step heights can be adjusted for these exercises to further increase (or decrease) the stability requirements of the exercise. When the body is upright, greater stability requirements would be expected in hip extension movements which may be reflected in this vector having the highest average EMG excitation level. However, differences in exercises mean that a wide range of EMG levels (6.1-86.0% MVIC) were found in this vector. Exercises with a greater base of stability (squats and lunges) may be implemented for more novice subjects while greater challenges can be imposed from step up exercises to the more advanced versions of single leg squats.

**Horizontal force vector (Anteroposterior)**

Fourteen exercises were performed in the anteroposterior force vector (average: 32.8% MVIC, highest mean: single leg bridge 54.2% MVIC). The bridge and its unilateral version were the two most used exercises (both in 6 studies) in this vector highlighting their prominence of application. The single leg bridge was found to elicit a higher range of Gmax EMG excitation level (32.6-54.2% MVIC) than the bridge (16.4-41.5% MVIC), most likely due to the greater demands (increased load required to be stabilized with one leg off the ground) imposed by a single leg base of support compared to the bilateral position. Low levels of excitation (< 20% MVIC) were found in bridging exercises where the feet are placed on a swiss ball or where subjects were required to perform a hamstring curl movement from a bridge position. Similarly, when performing a single leg bridge on a BOSU® surface, a lesser level of excitation (28.4% MVIC) was found compared to single leg bridge on the ground (32.6-54.2% MVIC). Therefore, it appears that when performing bridging exercises on an unstable surface (swiss ball or bosu), the level of Gmax excitation is decreased. When tactile and verbal cues to activate the glute muscle were given, EMG excitation levels increased (33.0% vs. 16.8% MVIC) compared to the regular bridge exercise, thus should be a consideration for practitioners especially during exercise instruction in novice clients. Five single leg bridge exercises elicited high excitation levels with differing positions from the leg and foot on the ground, and with the leg in the air, resulting in small changes in levels of EMG %MVIC. Although altering the positions can be used to change the Gmax excitation level, when the dominant knee (i.e. the leg in contact on the ground) was flexed to 135° instead of 90°, hamstring excitation decreased from 58-75% to 20-23% MVIC. Therefore, for subjects who may more readily recruit the hamstrings, altering the angle of the knee reduces hamstring excitation while Gmax levels remain relatively similar. However, hamstring activity was not assessed in this review. None of the exercises in this vector elicited a very high EMG amplitude, however, exercises in this vector may be suitable as early hip extension exercises as they provide a stable base of support with the body on the ground. Progression and difficulty can be increased by having the exercises performed unilaterally while being further challenged by extending the leg in the air. Performing bridging exercises on unstable surfaces decreases Gmax excitation and thus may be more suitable for targeting other muscles or goals. Additionally, compared to many of the vertical and posteranterior exercises, the exercises performed in this vector involve a change in body position resulting in a portion of body mass supported by the floor. This reduces the total load needing to be moved by the hip musculature.

**Horizontal force vector (Posteroanterior)**

Thirty-eight exercises were included in the posteranterior vector (average: 30.5% MVIC, highest mean: plank with bent leg hip extension 106.2% MVIC). Though this vector had the highest number of exercise variations, many of the exercises are similar with small changes in either hip angles or knee angles. Many of the exercise variations in this vector replicate the testing position used to obtain %MVIC, though this vector had the lowest average EMG %MVIC level. However, of all the exercises in this review, this vector had the highest individual excitation level found in the plank with bent leg hip extension resulting in 106.2% MVIC. This suggests that when the base of support is challenged in this position (i.e. a person is only supported from one foot and their elbows), Gmax excitation is greatly increased during hip extension from this position.
When performing hip extension from a quadruped position (i.e. starting with ground contact from the hands and knees), moderate to large excitation levels result. Whether the extended leg utilises knee flexion (32.2% MVIC) or extension (29.9% MVIC) resulted in similar values. However, when the non-dominant leg was assessed with knee flexion (21% MVIC), a difference was found compared to the dominant leg (59.7% MVIC). Though subject differences could be a factor to explain the findings between the studies, Selkowitz, Beneck, Powers used indwelling electrodes compared to surface electrodes which may also account for differences in results. When the arm was raised along with the leg during the quadruped exercise, the excitation level increased (56.2 % MVIC) most likely due to the greater stability challenge with less ground contact points for base support. Changes in excitation levels were also found from hip extension exercises performed with the hip in different positions. Performing hip extension from increased degrees of hip abduction (0° to 30°) was found to increase Gmax excitation by 9% and by 27% (0° to 15°, also with 20° hip external rotation). Furthermore, exercise performed from different hip flexion positions (0° to 20°) increased excitation by 3%, while hip extension from hip external rotation increased excitation by 10%. The position of the leg from the knee joint was also found to affect Gmax excitation levels, with Sakamoto, et al. finding that knee flexion (23.1% MVIC) elicited higher excitation than knee extension (12.7% MVIC).

Two studies using prone hip extensions exercises, found that Gmax excitation was increased (2-4%) when subjects performed abdominal drawing-in during the exercise. Similarly, when subjects braced their abdominals during prone hip extension, greater levels of excitation (4-15%) were found. Moreover, as found during bridging exercises, when subjects were instructed to activate their glutes during prone hip extension from 30° hip flexion, a greater level of Gmax excitation was found (21.6% vs. 9.7% MVIC) compared to the non-instructed version. Increased Gmax excitation was reported in reverse hyperextension (38.8% vs. 22.0%) and back/torso extensions (32.4% vs. 23.8%) when subjects performed a lumbopelvic control stabilisation strategy. These findings suggest that cueing internal mechanisms can be used to elicit greater Gmax excitation during different hip extension exercises. Exercise performed in this vector can be used to elicit a wide range of Gmax EMG excitation. Through altering positions of the hip (flexion, abduction, external rotation), greater excitation levels can be achieved with ground base stability. Moreover, by internal cueing mechanisms subjects can increase Gmax excitation during differing prone extensions exercises. Progression can be increased by challenging the base of support through contralateral and ipsilateral arm and leg raises during quadruped exercises, with greater challenge found during the plank base of support exercise.

**Limitations**

The reader should be cognizant of several limitations that affect interpretation and bias, namely that the methodological approaches varied greatly between the thirty-nine studies (see Appendix 1). Studies used different testing positions (standing, prone, supine) for determination of the MVIC, which could dramatically impact normalized levels of gluteal activation. Electrode placement (superior, inferior, mid-belly) also varied among studies. Several studies investigated the same exercise, however, differences in the way the exercises were performed need to be considered when analyzing the findings. For example, the step-up height used for step-up exercises ranged between 15.0 to 20.3 cm, therefore, differing levels of EMG activation would be an expected outcome. To most thoroughly compare EMG excitation between two studies, at the very least, their MVIC positions, electrode site placements, data processing, and amplitude presentations should be identical. Furthermore, other variables such as range of motion, relative load, effort and tempo should also be similar. This review examined muscular excitation through EMG analysis which itself has limitations when interpreting findings and providing practical suggestions. EMG is a useful tool for gaining insight into the neuromuscular system, musculoskeletal modelling, and basic science work though, its practical application is not truly clear, therefore, the reader needs to be cognizant of its limitations. However, despite these factors, EMG is a commonly implemented method into providing insights into
how the neuromuscular system behaves and may be used as guidance to assist in understanding musculature excitation. This review summarizes information obtained from healthy subjects; therefore, vigilance is necessary when extrapolating these findings to patients with pathology. Moreover, the heterogeneity of the subjects should be considered, with differences in gender, fat mass and training status potentially affecting the findings. The risk of bias should also be noted, with three of the studies failing to adequately describe the subject's characteristics.

CONCLUSIONS
Though several limitations exist within this review, some general observations can be made as follows: 1) body weight hip extension exercises provided a wide range of Gmax EMG excitation ranging from 6.1% to 106.2% MVIC; 2) when pooled as an average, similar levels of excitation were found between force vectors though the range of excitation levels differed between vectors; 3) unilateral exercises produced higher EMG values compared to the bilateral version of the same exercise; 4) females exhibited greater EMG excitation than males in all hip extension exercises, 5) verbal and tactile cues increase Gmax EMG excitation, while bracing and drawing-in the abdominals also increase excitation levels; and, 6) hip extension exercises performed in greater degrees/angles of hip flexion, hip abduction or hip external rotation result in higher measured EMG excitation levels. The pooled averaged values for the same exercises should be interpreted as a guideline and caution should be used for interpreting their findings with further research into each exercise with the same methodology required to verify these results. Moreover, this review focused on body weight exercises, therefore, whether the loaded version of the same exercises in this review results in similar findings requires investigation. When strengthening a weaker muscle or muscle group, practitioners may wish to prescribe a gradual and progressive exercise program to ensure the targeted area is developed. Practitioners should initially consider exercises performed in the horizontal vector as they provide a large base of support and are less challenging compared to vertical vector exercises. Moreover, bi-lateral exercises should be mastered before prescribing unilateral versions. This may be of importance if individuals seek and implement a compensatory movement pattern when faced with weakness or dysfunction. Individuals may benefit from being prescribed exercises that they can perform with good technique without substitution. Subsequently, once this can be achieved, exercise difficulty can be progressed with more demanding exercises.

REFERENCES


### Appendix 1. Summary of all studies reviewed with EMG excitation (%MVIC) values given as the mean and the standard deviation. (n = 39)

<table>
<thead>
<tr>
<th>Author and date</th>
<th>Subjects (Sex, age, height, mass)</th>
<th>Methodology (MVIC position and electrode site placement)</th>
<th>Hip extension exercises</th>
<th>Mean ± SD EMG excitation (%MVIC)</th>
<th>Quality Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worrell, Crip, LaRosa</td>
<td>Group 1: 6 males, 7 females (22 ± 8.6 years; 171 ± 15 cm; 69.1 ± 14.1 kg) Group 2: 13 males, 6 females (27.5 ± 5 years; 175 ± 9 cm; 73.3 ± 15.3 kg)</td>
<td>Prone hip extension against manual resistance at 0° of hip flexion. Placement half-way between the second sacral prominence and the greater trochanter of the femur.</td>
<td>Lateral step up (20 cm height)</td>
<td>20 ± 11 group 1 16 ± 7 group 2</td>
<td>11</td>
</tr>
<tr>
<td>Zeller, et al.</td>
<td>9 males (20.3 ± 3 years; 182 ± 5 cm; 78.8 ± 4.0 kg) 9 females (22 ± 8.6 years; 170 ± 6 cm; 64.3 ± 5.5 kg)</td>
<td>Prone hip extension against manual resistance with knee flexed at 90° Placement not specified.</td>
<td>Single leg squat</td>
<td>62.7 ± 43 male 81.2 ± 28 female</td>
<td>11</td>
</tr>
<tr>
<td>Ayotte, et al.</td>
<td>16 males, 7 females (31.2 ± 5.8 years; 173.1 ± 10.1 cm; 77.0 ± 13.9 kg)</td>
<td>Supine hip extension against fixed resistance pad placed proximal to the popliteal fossa from 30° hip flexion. Placement 1/3 of the distance from the second sacral vertebra to the greater trochanter.</td>
<td>Forward step up (15.2 cm height) Lateral step up (15.2 cm height) Retro step up (15.2 cm height) Single leg mini squat (15.2 cm depth) Single leg wall squat, other leg knee extended</td>
<td>74 ± 43 56 ± 29 59 ± 35 57 ± 43 86 ± 43</td>
<td>14</td>
</tr>
<tr>
<td>Ekstrom, Donatelli, Carp</td>
<td>19 males, 11 females (27 ± 8 years; 176 ± 8 cm; 74 ±11 kg)</td>
<td>Prone hip extension against manual resistance applied above the knee with knee flexed to 90° Placement between the lateral edge of the sacrum and the posterosuperior edge of the greater trochanter.</td>
<td>Bridge Lateral step up (20.3 cm height) Lunge Quadruped hip extension with arm raise Single leg bridge</td>
<td>25 ± 14 29 ± 13 36 ± 17 56.2 ± 22 40 ± 20</td>
<td>12</td>
</tr>
<tr>
<td>Ekstrom, Osborn, Hauer</td>
<td>27 males, 32 females (age range 21-35 years)</td>
<td>Prone hip extension against manual resistance applied just above the knee with knee flexed at 90° Placement between the lateral edge of the sacrum and the posterosuperior edge of the greater trochanter.</td>
<td>Bridge Bridge with knees extended and feet on a swiss ball</td>
<td>27 ± 13 20 ± 14</td>
<td>11</td>
</tr>
<tr>
<td>Farrokhi, Pollard, Souza, et al.</td>
<td>5 males, 5 females (26.7 ± 3.2 years)</td>
<td>Prone hip extension against strap resistance positioned superior to the knee joint with the knee flexed to 90° Placement midway between the second sacral vertebra and the greater trochanter.</td>
<td>Lunge Lunge with trunk extension Lunge with trunk flexion</td>
<td>18.5 ± 11.0 19.3 ± 11.8 22.3 ± 12.0</td>
<td>12</td>
</tr>
<tr>
<td>Boudreaux, Dwyer, Mattacola, et al.</td>
<td>22 males, 22 females (23.3 ± 5.1 years; 174.5 ± 9.1 cm; 74.6 ± 16.5 kg)</td>
<td>Standing hip extension against strap resistance placed around the distal third of the thigh with knee flexed to 90° Placement half the distance between the greater trochanter of the femur and the spinous process of the second sacral vertebra along an oblique angle at the level of the greater trochanter.</td>
<td>Forward step-up and over (20.3 cm height) Lunge Single leg squat</td>
<td>16.5 ± 11.7 21.7 ± 14.7 35.2 ± 24.0</td>
<td>14</td>
</tr>
<tr>
<td>Distefano, Blackburn, Marshall, et al.</td>
<td>9 males, 12 females (22 ± 3 years; 171 ± 11 cm; 70.4 ± 15.3 kg)</td>
<td>Prone hip extension against manual resistance with knee flexed at 90° Placement 1/3 of the distance between the second sacral vertebra and the greater trochanter.</td>
<td>Lunge Lateral lunge Transverse lunge Single leg deadlift Single leg squat</td>
<td>44 ± 23 41 ± 20 49 ± 20 59 ± 28 59 ± 27</td>
<td>12</td>
</tr>
</tbody>
</table>
Appendix 1. Summary of all studies reviewed with EMG excitation (%MVIC) values given as the mean and the standard deviation. (n=39) (continued)

<table>
<thead>
<tr>
<th>Author and date</th>
<th>Subjects (Sex, age, height, mass)</th>
<th>Methodology (MVIC position and electrode site placement)</th>
<th>Hi+ extension exercises</th>
<th>Mean ± SD EMG excitation (%MVIC)</th>
<th>Quality Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis, Sahrman &amp; al.</td>
<td>11 females (27.7 ± 6.2 years; 165.2 ± 3.6 cm; 62.3 ± 6.9 kg)</td>
<td>Prone hip extension against manual resistance with knee flexed at 90° Placement on the muscle belly.</td>
<td>Prone hip extension from hip flexion of 30° Prone hip extension from hip flexion of 30° with verbal cues to activate the glutes Prone hip extension from hip flexion of 30° with verbal cues to activate the hamstrings</td>
<td>9.7 ± 2.9 21.6 ± 9.8 11.2 ± 5.2</td>
<td>12</td>
</tr>
<tr>
<td>Sakamoto, et al.</td>
<td>16 males, 15 females (24.5 ± 3.5 years; 170.0 ± 9.0 cm; 66.9 ± 11.9 kg)</td>
<td>Prone hip extension against manual resistance with knee extension Placement 1/3rd of the distance between the second sacral vertebra and the greater trochanter.</td>
<td>Prone hip extension with knee extension Prone hip extension with 90° knee flexion Prone hip extension with lateral hip rotation and knee extension Prone hip extension with lateral hip rotation and knee flexion</td>
<td>12.7 ± 8.6 23.1 ± 21.2 22.5 ± 10.4 21.2 ± 12.0</td>
<td>12</td>
</tr>
<tr>
<td>Lubahn, Kernozek, Tyson, et al.</td>
<td>18 females (22.3 ± 2.3 years; 166.8 ± 9.2 cm; 61.1 ± 7.1 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement on the muscle belly.</td>
<td>Forward step up (Height unknown) Single leg squat Squat</td>
<td>36.4 ± 18.6 47.4 ± 21.2 21.7 ± 15.8</td>
<td>12</td>
</tr>
<tr>
<td>Boree, et al.</td>
<td>24 (Anthropometrical details not provided)</td>
<td>Prone hip extension against a strap with the knee flexed at 90° Placement not specified.</td>
<td>Forward step up (20 cm height) Lateral step up (15 cm height) Plank with bent leg hip extension Skater squat Single leg bridge Single leg deadlift Single leg squat Quadruped bent leg hip extension DOM Quadruped bent leg hip extension non-DOM</td>
<td>54.7 63.8 106.2 66.2 54.2 58.8 70.7 59.7 21.0</td>
<td>10</td>
</tr>
<tr>
<td>Bouillon, Wilhelm, Eisel, et al.</td>
<td>20 males, 20 females (22 ± 1 years; 170 ± 10 cm; 65 ± 13 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement inferior and medial to a line drawn between the PSIS and the posterior greater trochanter.</td>
<td>Lateral lunge Lunge</td>
<td>12 ± 3 11 ± 2.5</td>
<td>12</td>
</tr>
<tr>
<td>Nakagawa, et al.</td>
<td>20 males (23.5 ± 3.8 years; 176 ± 6.1 cm; 74.6 ± 9.1 kg) 20 females (21.8 ± 2.6 years; 163 ± 7.3 cm; 59.4 ± 7.3 kg)</td>
<td>Prone hip extension against strap with the knee flexed at 90° Placement parallel to the mid-muscle belly.</td>
<td>Single leg squat</td>
<td>24.6 ± 2.7 females 18.9 ± 8.9 males</td>
<td>12</td>
</tr>
<tr>
<td>Tateuchi, Taniguchi, Mori, et al.</td>
<td>10 males, 6 females (24.3 ± 5.2 years; 165.7 ± 7.9 cm; 59.0 ± 8.0 kg)</td>
<td>Prone hip extension against manual resistance. Placement halfway on the line extending between the sacrum and greater trochanter.</td>
<td>Prone hip extension from 30° hip flexion to 10° hip extension</td>
<td>10.9 ± 3.3</td>
<td>10</td>
</tr>
<tr>
<td>De Ridder et al.</td>
<td>8 males, 6 females (24.7 ± 3.2 years; 172.9 ± 6.4 cm; 64.5 ± 12.5 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement midway between the posterouterior iliac spine and the ischial tuberosity.</td>
<td>Prone back/torso extension Reverse hyperextension</td>
<td>44.9 concentric 33.1 eccentric 30.5 concentric 20.5 eccentric</td>
<td>12</td>
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<tr>
<td>Kang, et al.</td>
<td>18 males, 12 females (22.8 ± 2.9 years; 170.3 ± 4.1 cm; 66.9 ± 10.8 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement halfway between the greater trochanter and second sacral vertebra in the middle of the muscle and at an oblique angle.</td>
<td>Prone hip extension with knee flexion with hip abducted 0° Prone hip extension with knee flexion with hip abducted 15° Prone hip extension with knee flexion with hip abducted 30°</td>
<td>20.2 ± 8.6</td>
<td>11</td>
</tr>
<tr>
<td>Lee, Ko, Lim 88</td>
<td>20 males (22.9 ± 2.1 years; 174.4 ± 3.9 cm; 70.0 ± 6.2 kg)</td>
<td>Side-lying hip abduction against suprapelvic resistance with the hip in 90° abduction Placement 1/3rd of the distance between the second sacral vertebra and the greater trochanter.</td>
<td>Lunge Lunge with compression pelvic belt Single leg deadlift Single leg deadlift with compression pelvic belt Single leg squat Single leg squat with compression pelvic belt</td>
<td>11.5 ± 6.9</td>
<td>12</td>
</tr>
<tr>
<td>Webster, Gribble 89</td>
<td>1 male, 8 females (22.9 ± 4.5 years; 164 ± 6.5 cm; 65.4 ± 10 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement half-way between the second sacral prominence and the greater trochanter of the femur.</td>
<td>Single leg squat with rotation Transverse lunge</td>
<td>78 ± 45</td>
<td>12</td>
</tr>
<tr>
<td>Bolgla, et al. 89</td>
<td>18 males (24.3 ± 3.4 years; 180 ± 10 cm; 81.2 ± 9.7 kg) 16 females (24.0 ± 1.5 years; 165 ± 10 cm; 59.9 ± 8.8 kg)</td>
<td>Prone hip extension against strap with the knee flexed at 90° Placement parallel alignment over the belly.</td>
<td>Single leg wall slide, other leg knee flexed Single leg mini-squat Lateral step down (20 cm height) Forward step down (20 cm height)</td>
<td>21.6 male 32.0 female</td>
<td>12</td>
</tr>
<tr>
<td>Holiman, Galardi, Lin, et al. 90</td>
<td>41 females (18-36 years)</td>
<td>Prone hip extension against strap with the knee flexed at 90° Placement at one-half the distance between the sacrum and greater trochanter.</td>
<td>Single leg squat</td>
<td>20.9-23.8</td>
<td>11</td>
</tr>
<tr>
<td>Esmami, Arab, Ghamikhar 91</td>
<td>10 males (22.5 ± 3.8 years; 177 ± 7 cm; 74.1 ± 8.6 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement at the midpoint of a line running from S2 to the greater trochanter.</td>
<td>Prone hip extension with knee extension</td>
<td>18.5 ± 12.1</td>
<td>12</td>
</tr>
<tr>
<td>Macaskill, Dunari, Wallace 92</td>
<td>14 males, 20 females (21.5 ± 1.7 years; 170.5 ± 11 cm; 67.6 ± 7.5 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement 1/3rd of the distance between the second sacral vertebra and the greater trochanter.</td>
<td>Forward step up (15 cm height) Lateral step up (15 cm height)</td>
<td>28.7 ± 18.7</td>
<td>11</td>
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<tr>
<td>Park, Yoo 93</td>
<td>18 males (21.9 ± 2.2 years; 175.1 ± 5.3 cm; 66.6 ± 8.4 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement at half the distance between the trochanter and the sacral vertebrae in the middle of the muscle on an oblique angle.</td>
<td>Back/torso extension with extended knees and hands across chest Back/torso extension with extended knees and hands behind head Back/torso extension with flexed knees 90° and hands across chest Back/torso extension with flexed knees 90° and hands behind head</td>
<td>28.3 ± 14.5 26.5 ± 13.6 34.8 ± 20.6 36.6 ± 22.6</td>
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<tr>
<td>Suhr, et al. 32</td>
<td>21 males (20.2 ± 0.4 years; 171.1 ± 5.0 cm; 64.3 ± 10.5 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement halfway between the greater trochanter and the second sacral vertebra.</td>
<td>Prone hip extension with 90° knee flexion and neutral hip position Prone hip extension with 90° knee flexion and 15° hip abduction Prone hip extension with 90° knee flexion and 15° hip abduction and 20° hip external rotation</td>
<td>14.1 ± 9.4 22.5 ± 13.6 41.0 ± 23.6</td>
<td>11</td>
</tr>
<tr>
<td>Kim, Kim 34</td>
<td>14 males, 16 females (24.7 ± 3.2 years; 167.5 ± 8.2 cm; 61.5 ± 6.9 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement 1/3rd the distance between the second sacral vertebrae and the greater trochanter.</td>
<td>Prone hip extension to 10° Prone hip extension to 10° with abdominal drawing-in Prone hip extension to 10° with pelvic tilt &gt; 15° Prone hip extension to 10° with abdominal drawing-in with pelvic tilt &gt; 15°</td>
<td>23.9 ± 18.5 24.4 ± 14.3 32.5 ± 21.3 45.9 ±33.7</td>
<td>11</td>
</tr>
<tr>
<td>Kim, Yoo 35</td>
<td>18 males (23.3 ± 1.8 years; 177.4 ± 5.3 cm; 74.2 ± 7.2 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement not specified.</td>
<td>Prone hip extension with upper body on table Prone hip extension with body on floor</td>
<td>62.3 ± 27.1 56.5 ± 20.2</td>
<td>11</td>
</tr>
<tr>
<td>Mills, Frank, Goto, et al. 36</td>
<td>20 females (Anthropometrical details not provided)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement 1/3rd the distance between the second sacral vertebrae and the greater trochanter</td>
<td>Squat</td>
<td>12.4 ± 6.3</td>
<td>11</td>
</tr>
<tr>
<td>Yoon, Lee, An 37</td>
<td>15 subjects (26.7 ± 3.7 years; 167.1 ± 9.2 cm; 58.1 ± 11.7 kg)</td>
<td>MVIC position not specified Placement not specified</td>
<td>Prone hip extension from 0° hip flexion Prone hip extension from 15° hip flexion Prone hip extension from 30° hip flexion</td>
<td>19.7 ± 7.9 22.5 ± 9.4 18.9 ± 7.8</td>
<td>11</td>
</tr>
<tr>
<td>Youdas, Hartman, Murphy, et al. 38</td>
<td>13 males (23.4 ± 1.2 years; 180 ± 10 cm; 79.7 ± 10.6 kg) 13 females (23.5 ± 1.2 years; 170 ± 10 cm; 63.7 ± 7.4 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement on the muscle belly, parallel to the line of action.</td>
<td>Bridge Bridge with feet on swiss ball Single leg bridge Single leg bridge with foot on bosa Bridge with hamstring curl Bridge with feet on swiss ball and hamstring curl</td>
<td>16.4 13.0 32.6 28.4 18.5 10.9</td>
<td>12</td>
</tr>
<tr>
<td>Chon, Bok, Cho, et al. 39</td>
<td>14 males, 13 females (22.8 ± 5.8 years; 166.4 ± 10.1 cm; 66.2 ± 13.4 kg)</td>
<td>MVIC position not specified Placement between the sacrum and greater trochanter</td>
<td>Bridge Single leg bridge Single leg bridge (raised leg abducted to 30°)</td>
<td>41.5 ± 16.4 47.5 ± 16.0 46.7 ± 12.0</td>
<td>11</td>
</tr>
<tr>
<td>Jeon, et al. 32</td>
<td>16 males (25.4 ± 4.2 years; 174.7 ± 2.8 cm; 73.1 ± 2.1 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement at the midpoint of the line extending between the greater trochanter and sacrum</td>
<td>Prone hip extension with upper body on table Prone hip extension with upper body on table and abdominals drawing-in Prone hip extension with upper body on table and flexed contralateral knee joint on a chair</td>
<td>43.9 ± 16.1 47.5 ± 19.8 66.4 ± 25.8</td>
<td>12</td>
</tr>
<tr>
<td>Lee, Song, Kwon 38</td>
<td>10 males, 10 females (21.1 ± 1.8 years; 168.7 ± 8.3 cm; 66.1 ± 12.3 kg)</td>
<td>MVIC method not specified. Placement at 50% on the line between the sacral vertebrae and the greater trochanter</td>
<td>Squat with 0° trunk flexion Squat with 15° trunk flexion Squat with 30° trunk flexion</td>
<td>6.1 ± 4.0 6.3 ± 4.0 8.0 ± 4.9</td>
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| Selkowitz, Beneck, Powers 28 | 10 males, 10 females (27.9 ± 6.2 years; 170.5 ± 11.1 cm; 67.7 ± 14.1 kg) | Four conditions normalised to whichever contraction elicited greater EMG excitation: 1) Prone hip extension of 45° with the knee flexed at 90° against strap resistance. 2) Prone hip extension of 0° with the knee flexed at 90° against strap resistance. 3) Sidelying position with hip in 30° abduction and knee extended against strap. 4) As position 3 with hip in 45° flexion. Placement Gmax (S) inserted superior and lateral to the midpoint of a line drawn between the posterior superior iliac spine and the posterior greater trochanter, Gmax (I) inserted inferior and medial to the midpoint of the same line, such that it was 2.5 to 5.0 cm above the gluteal fold. | Bridge  
Forward step up  
Lunge  
Single leg bridge  
Squat  
Quadraped hip extension with knee extended  
Quadraped hip extension with knee flexed | | 12 |
| Chan, et al. 27 | 10 males, 10 females (21.1 ± 1.7 years; 166.8 ± 7.9 cm; 58.1 ± 9.2 kg) | Prone hip extension against manual resistance with the knee flexed at 90°. Placement 1/3rd of the distance from iliac crest to greater trochanter, starting from greater trochanter. | Prone hip extension up to 20° with 90° knee flexion  
Prone hip extension up to 20° with 90° knee flexion with abdominal bracing | | 12 |
| Hollman, et al. 29 | 15 females (23.3 ± 1.7 years; 169.4 ± 8.3 cm; 62.6 ± 6.7 kg) | Prone hip extension against strap resistance with the knee flexed at 90°. Placement halfway between the sacral vertebrae and the greater trochanter | Bridge  
Bridge with verbal and tactile cueing | | 13 |
| Lehecka, et al. 30 | 12 males, 16 females (23.4 ± 2.3 years; 173 ± 11 cm; 72.6 ± 13.9 kg) | Prone hip extension against strap resistance with the knee flexed at 90°. Placement anterosuperior to Gmax, inferior to the lateral aspect of the iliac crest on a line towards the greater trochanter on the muscle belly. | Single leg bridge. DOM leg 90° knee flexion with foot flat. Non-DOM leg knee extended Single leg bridge. DOM leg 135° knee flexion with foot flat. Non-DOM leg knee extended Single leg bridge. DOM leg 90° knee flexion with foot flat. Non-DOM leg knee relaxed in flexion and femur vertical Single leg bridge. DOM leg 90° knee flexion with dorsiflexed ankle. Non-DOM leg knee relaxed in flexion and femur vertical Single leg bridge. DOM leg 135° knee flexion with dorsiflexed ankle. Non-DOM leg knee relaxed in flexion and femur vertical | | 11 |
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<tbody>
<tr>
<td>Van Oosterwijk, et al. 38</td>
<td>4 males, 9 females (22.6 ± 2.1 years; 172 ± 7.3 cm; 61.3 ± 9.5 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement midway between the posterosuperior iliac spine and the ischial tuberosity.</td>
<td>Prone back/torsion extension without lumbopelvic control strategy Prone back/torsion extension with lumbopelvic control strategy Reverse hyperextension without lumbopelvic control strategy Reverse hyperextension with lumbopelvic control strategy</td>
<td>23.8 ± 10.1 32.4 ± 21.6 22.0 ± 7.7 38.8 ± 24.1</td>
<td>12</td>
</tr>
<tr>
<td>Youdas, et al. 2</td>
<td>13 males, 13 females (23.5 ± 1.2 years; 175.0 ± 10.0 cm; 71.7 ± 9.0 kg)</td>
<td>Prone hip extension against manual resistance with the knee flexed at 90° Placement parallel to the muscle’s line of action.</td>
<td>Single leg bridge Supine manual resisted hip extension</td>
<td>33.8 34.7</td>
<td>12</td>
</tr>
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BM = body mass, DOM = dominant, EMG = electromyography, Gmax = Gluteus Maximus, I = inferior, MVIC = maximum voluntary isometric contraction, ROM = range of motion, S = superior
ABSTRACT

Background: Anterior knee pain during knee extension may be related to a meniscal movement restriction and increased meniscal load during function. One method of treatment involves the use of manual posterior mobilization of the tibia to specifically target the meniscotibial interface of the knee joint.

Purpose: The purpose of this study was to measure motion at a cadaveric medial meniscus anterior horn during a posterior tibial mobilization.

Study Design: Prospective, multifactorial, repeated–measures laboratory study.

Methods: Eight unembalmed cadaveric knee specimens were mounted in a custom apparatus and markers were placed in the medial meniscus, tibia and femur. The tibia was posteriorly mobilized in two randomized knee positions (0 degrees and 25 degrees) using three randomly assigned loads (44.48N, 88.96N, and 177.93N). Markers were photographed and digitally measured and analyzed.

Results: All load x position conditions produced anterior displacement of the meniscus on the tibia, where the displacement was significant \( t(7) = -3.299; p = 0.013 \) at 0 degrees loaded with 177.93N (mean 0.41 ± 0.35 mm). The results of 2(position) x 3(load) repeated measures ANOVA for meniscotibial displacement produced no significant main effects for load \( F (2,14) = 2.542; p = 0.114 \) or position \( F (1,7) = 0.324, p = 0.587 \). All load x position conditions produced significant posterior tibial and meniscal displacement on the femur. The 2(position) x 3(load) repeated measures ANOVA revealed a significant main effect for load for both femoral marker displacement relative to the tibial axis \( F (2,14) = 77.994; p < 0.001 \) and meniscal marker displacement relative to the femoral marker \( F (2,14) = 83.620; p < 0.001 \).

Conclusion: Use of a mobilization technique to target the meniscotibial interface appears to move the meniscus anteriorly on the tibia. It appears that this technique may be most effective at the end range position.

Level of Evidence: 2 (laboratory study)

Keywords: Anterior knee pain, Knee, Meniscus

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**ORIGINAL RESEARCH**

**THE EFFECTS OF POSTERIOR TIBIAL MOBILIZATION ON MENISCAL MOVEMENT: AN IN-SITU INVESTIGATION**

Susan Lilly, PT, ScD
Gesine H. Seeber, PT, MS
Michael P. Smith, ATC, PhD
Janna M. McGaugh, PT, ScD
C. Roger James, PhD
Jean-Michel Brismée, PT, ScD
Phillip S. Sizer, PT, PhD

**IJSPT**

**ABSTRACT**

**Background:** Anterior knee pain during knee extension may be related to a meniscal movement restriction and increased meniscal load during function. One method of treatment involves the use of manual posterior mobilization of the tibia to specifically target the meniscotibial interface of the knee joint.

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Phillip S. Sizer Jr. PT, PhD, OCS, FAAOMPT
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INTRODUCTION
Anterior knee pain is a common patient complaint that can occur in response to several different pathologies including but not limited to intraarticular pathology, patellofemoral pain syndrome, plica syndrome, infrapatellar fat pad disorders, and apophysitis.1-7 Treating anterior knee pain with limited knowledge of the specific pathology can give rise to variable responses and outcomes to common interventions.8,9 Pathology of the meniscus, particularly at the anterior horn, may produce anterior knee pain. Pereira et al10 and Mine et al11 identified free nerve endings and nerve endings positive for substance P in the meniscus anterior horn, suggesting a pain-generating role. Moss et al12 described an anterior knee pain management strategy aimed at the meniscus as the pain generator. These authors reported pain reduction when implementing a program that included mobilization to the meniscus. If the meniscus cannot sufficiently clear the anterior rolling femur in the closed kinematic chain, pain may result secondary to increased pressure on the anterior horn.

Orthopedic manual therapy (OMT) techniques designed to encourage meniscal movement between the femur and tibia have been proposed.3,13-15 Anterior meniscal translation on the tibia, resulting from OMT, can facilitate moving the meniscus out of the way of the anterior rolling femur during extension (Figure 1). Because the meniscus cannot be manually accessed in vivo in an isolated non-surgical fashion, clinicians can incorporate a manually-applied posterior mobilization force to the tibia in order to facilitate meniscal anterior displacement on the tibia. As the tibia and meniscus translate posterior during the posterior tibial mobilization, the meniscus is thought to come in contact with the femur, preventing further meniscal movement but allowing continued posterior tibial translation. In this case, the net effect would be a relative anterior meniscal displacement on the tibia (Figure 1). However, this mechanical response of the meniscus to manual posterior tibial mobilization has not been mechanically examined.

The purpose of this study was to measure motion at a cadaveric medial meniscus anterior horn (MMAH) during a posterior tibial mobilization. The investigators hypothesized that with a manually applied posterior tibial force with the femur posteriorly supported, the MMAH would significantly move anterior in relation to the tibia, accompanied by significant movement of the tibia in relation to the femur. Additionally, the investigators hypothesized that the MMAH would not move significantly with respect to the femur. This experiment incorporated the effects of two different knee angles and three different mobilization forces on MMAH motion.

METHODS
Design
The investigators implemented a prospective study using a 2 (knee position angle) x 3 (load intensity) multifactorial, repeated–measures design. The following dependent variables were evaluated:

1. Mensical Marker Displacement: Changes in perpendicular distance (mm) between the meniscal marker and the tibial axis.
2. Femoral Marker Displacement: Changes in perpendicular distance (mm) between the femur marker and the tibial axis.

3. Meniscal Minus Femur Marker Displacement: Changes in the difference between perpendicular distance (mm) of the MMAH marker to the tibial axis and femoral marker to the tibial axis.

The following independent variables were used in the study:

1. Knee position angle (two levels):
   a. 0 degrees of flexion (0 deg)
   b. 25 degrees of flexion (25 deg)

2. Load intensity (three levels):
   a. 44.48 Newtons (44.48 N)
   b. 88.96 Newtons (88.96 N)
   c. 177.93 Newtons (177.93 N)

These independent variables produced a total of six load x position conditions:

- **Condition 1**: 0 deg 44.48 N = 0 degrees flexion, 44.48 Newtons load
- **Condition 2**: 0 deg 88.96 N = 0 degrees flexion, 88.96 Newtons load
- **Condition 3**: 0 deg 177.93 N = 0 degrees flexion, 177.93 Newtons load
- **Condition 4**: 25 deg 44.48 N = 25 degrees flexion, 44.48 Newtons load
- **Condition 5**: 25 deg 88.96 N = 25 degrees flexion, 88.96 Newtons load
- **Condition 6**: 25 deg 177.93 N = 25 degrees flexion, 177.93 Newtons load

Posterior tibial mobilization is commonly used to gain flexion of tibia on femur, as it promotes the appropriate arthrokinematic tibial translation occurring when the knee is actively flexed in the open kinematic chain. In addition, if the knee is placed in full available extension and the applied mobilization produces anterior meniscus displacement (as proposed in the present study), then a posterior tibial mobilization could be suited for gaining full, pain-free knee extension. Thus, both fully extended (0 deg) and slightly flexed (25 deg) knee positions were incorporated to evaluate this effect and to respect changes in joint congruency that occur at the end of knee extension on the proposed responses. Silvernail et al reported that approximately 45 N of posterior tibial force was needed to create a Maitland grade III OMT maneuver aimed at restoring knee extension. Conversely, the present authors’ pilot testing of mobilization forces that they clinically incorporate for treating the meniscotibial interface at end-range knee extension revealed that 177.93 N force was needed to reach end-range of posterior translation during the OMT mobilization technique under investigation. On that basis, the authors decided to use three different force values to measure a broader spectrum of responses: 44.48 N based on previous evidence regarding grade III Maitland mobilization; the present authors’ preferred clinically force (177.93 N); and the 88.96 N value resting halfway between both the other two values.

**Specimens**

A total of eight cadaveric knee specimens were harvested from unembalmed cadavers that were previously donated by the local university willed body program. The average age of the specimens was 79 years. The specimens were previously stored at -80 degrees Fahrenheit, then thawed overnight to room temperature prior to experimental use. Cadaveric specimens were excluded if they demonstrated observable meniscal abnormalities or damage during visual inspection.

**Instrumentation**

Specimens were prepared by removing cutaneous and subcutaneous tissue to expose the bony regions while leaving the joint capsule-ligamentous and retinacular structures intact. A 1 cm x 1 cm tissue window was cut in the specimen’s medial joint capsule to allow for visualization of the MMAH. A commercially available Phillips-type screw was inserted into the MMAH (meniscal marker). Additionally, Phillips-type screws were inserted into the distal medial femoral bone (femoral marker) and proximal medial tibia (tibial marker 1), each 5 cm from the medial joint line. Another Phillips-type screw was
placed 2 cm more distal on the medial tibia (tibial marker 2), allowing both tibial screws to create a reference line (tibial axis) for computing meniscal and femoral translations, as well as angular tibial motion all in the sagittal plane. Specimens were mounted in a custom wooden frame (Figure 2). The investigators insured that all markers and the ruler were positioned in the same plane to reduce error from differences in the depth of each image component. The wooden frame was securely attached to a table with clamps. The specimens were mounted in the frame by passing metal rods through the bony midshaft of both femur and tibia eight centimeters from the cut end of the bones. Bolts were used to secure the rods (not the bones) to the frame, which standardized the specimen position and minimized rotation in the transverse plane. The proximal end of the tibia remained completely unconstrained, so to allow a posterior mobilization force to create the observed tibial movements. The proximal end of the femur was secured with bolts but allowed positioning within the frame at either 0 deg knee flexion or 25 deg knee flexion. Knee position was measured with a standard goniometer. Stabilizing sandbags were positioned on the table, posterior to the distal femur.

The following principles were considered in order to ensure measurement validity during uniplanar image analysis: (1) the camera was aligned perpendicular to the testing plane, (2) sufficient focal distance was maintained through all measurements, and (3) an object of known dimension was present within the field of view to be later used for calibration purposes. A standard ruler of 25 cm length was attached vertically to the tibial side of the wooden frame, which served as a coordinate and scaling reference during measurement (Figure 2). Marker displacement was photographed using a 6.3-megapixel digital camera (FinePix S7000, fujiFilm, Fuji Photo Film Co., Ltd. 26-30, Nishiazabu 2-chome, Minato-Ku, Tokyo 106-620, Japan) and a room light source. The camera was placed one meter from the plane of the previously described ruler, with the focal point parallel to and centered with the specimen’s medial joint line. The camera was manually focused before image capture of each specimen. The marker position was captured and digitally analyzed (digitized) using uniplanar image analysis methods that have previously demonstrated reliability (intra- and intertester) and validity for measuring structural relationships and responses at different joint locations in different controlled laboratory settings.

Testing Procedure
The investigator performing the OMT technique had over five years of experience in routinely using the mobilization procedure. Each specimen was tested under each condition, where the order of conditions was randomly assigned, first by position then by load intensity. Distance from the reference ruler to each
marker was measured and recorded. Once positioned, a glide mobilization force was manually applied to the anterior tibia at the tibial tubercle in a posterior direction relative to the femur and parallel to the tibial plateau. The 44.48, 88.96, or 177.93 N force was measured by a hand-held dynamometer (MICROFET2, Hoggan Health Industries, Inc., Medical Products Division, Draper, UT) through the mobilization hand. A digital image was captured in an unloaded state (pre-load). The glide force was then applied and held for 60 seconds. A second digital image was captured at the end of the 60-second glide force while the load was sustained (post-load; Figure 2). This was repeated three times for each condition with a 60-second rest period between glide mobilization forces. Specimen # 2 and specimen # 8 were tested twice due to poor focus of the images. This second testing was not performed consecutively in relation to the first testing, where the order of conditions was again randomized.

At the end of testing, each specimen was dissected to ensure the meniscus marker was located in the anterior horn of the medial meniscus and to examine any meniscal abnormalities. In all eight specimens, the meniscus marker was correctly positioned and there were no observable meniscal abnormalities.

**Data Reduction**

The digital images were uploaded into a custom MATLAB analysis program (v.7.11.0, R2010b, The Mathworks, Inc., Natick, MA), where a single examiner manually digitized the marker coordinates. First, a 10-20 cm section of the aforementioned standard ruler was used within MATLAB data processing to calibrate subsequent measures. The raw data were used to determine marker position changes and displacement changes. The two tibial markers represented the reference line (tibial axis) for meniscal and femoral x and y coordinates. The perpendicular distance between the meniscal marker and the tibial axis represented meniscal marker positions. The perpendicular distance between the femoral marker and the tibial axis represented femoral marker positions. The difference between the meniscal marker and femoral marker positions represented the meniscus – femoral marker position.

The following formulated process was used to establish each marker position:

1. The slope-intercept form \( y = mx + b \) of the line defined by the two markers on the tibia was established.
2. A point not on the line (e.g. meniscus marker) and a slope perpendicular to the tibia was used to calculate the slope-intercept form of the perpendicular line.
3. The two line-equations were solved simultaneously to calculate the coordinate of the point where they intersect.

Using this process, the marker position computation for each marker was conducted by calculating the perpendicular distance \( r \) of the marker (e.g. meniscus marker) from the point not on the line to the point where the lines intersect. The formula for calculating the perpendicular distance was represented by:

\[
 r = \sqrt{(X^2 - X')^2 + (Y^2 - Y')^2}
\]

*Where x and y are the coordinates of the two points.*

Marker displacement was represented by changes in marker position in response to applied loads (Figure 3). For marker displacement (meniscal, femoral, or meniscal-femoral) at 0 deg knee flexion, the following formula was used to quantify the displacement:

\[
 \text{Marker Displacement} = \text{Marker position (0 deg X N)} - \text{Marker position (0 deg 0 N)}
\]

*Where X = 44.48, 88.96 or 177.93 N.*

For marker displacement (meniscal, femoral, or meniscal-femoral) at 25 deg knee flexion, the following formula was used to quantify the displacement:

\[
 \text{Marker Displacement} = \text{Marker position (25 deg X N)} - \text{Marker position (25 deg 0 N)}
\]

*Where X = 44.48, 88.96 or 177.93 N.*

**Statistical Analysis**

Descriptive and inferential statistical analyses were conducted using the SPSS (v.18.0 for Mac 10.6x; IBM Corp, Armonk NY, USA) software. Tests for data normality were conducted using the Shapiro-Wilk Test. Alpha level was set at 0.05 for significance throughout all tests.
The investigators first determined if the markers moved from a starting position to an end position (marker displacement) under a posterior tibial load. Mean and standard deviation (SD) values were calculated for changes in position for each marker. All data met the criteria for normality except femur position at 0 deg 88.96 N, as well as 0 deg 177.93 N. A non-parametric, Wilcoxon Signed Ranks Test was utilized for analyzing these data. Otherwise, separate 2-tailed dependent t-tests were used to analyze marker position differences in unloaded (0 N) versus loaded conditions (44.48, 88.96 or 177.93 N) at both knee angles. These tests were conducted for changes in: (1) meniscal marker position relative to tibial axis (representing a meniscotibial interface response); (2) femur marker position relative to tibial axis (representing a tibiofemoral interface response); and (3) meniscus minus femur marker position (representing a meniscofemoral interface response).

Secondly, through the statistical analysis the investigators assessed for differences in the extent of marker displacement across conditions. A separate 2 (knee position angle) x 3 (load intensity) repeated measures analysis of variance (ANOVA) was used to assess differences across conditions in: (1) meniscal marker displacement relative to tibial axis; (2) femoral marker displacement relative to tibial axis; and (3) meniscal marker displacement relative to femoral marker. Pairwise post-hoc comparisons were performed to assess for location of significant differences.

Third, through the statistical analysis the investigators tested for differences in tibial angle across conditions. Tibial angle data were analyzed using a 2 (knee position angle) x 3 (load intensity) repeated measures ANOVA to determine if any angular change occurred between the femur and the tibia during the different conditions. Pairwise post-hoc comparisons were performed to assess for location of significant differences.

RESULTS

Specimen

A total of eight unembalmed frozen cadaveric knee specimens were considered and retained, with no
cadavers being excluded from the study in response to the exclusion criteria.

Digital images
A total of 36 images were captured per specimen, based on three trials each for two loading conditions (pre-load vs. post-load) at three load intensities (44.48 N vs. 88.96 N vs. 177.93 N) in two knee positions (0 deg vs. 25 deg). Overall, 288 images were analyzed via MATLAB as previously described.

Meniscal Marker Displacement
At both knee positions, all load x position conditions produced anterior displacement of the meniscal marker relative to the tibial axis (Table 1). The results of the paired samples t-tests for meniscus displacement relative to the tibial axis found that only the condition 3 pre-load – post-load computation (0 deg 0 N – 0 deg 177.93 N) demonstrated a significant anterior meniscal marker displacement $[t(7) = -3.299; p = 0.013]$ (Table 2). Therefore, the hypothesis of significant movement of the MMAH relative to the tibia was only supported under condition 3 (0 deg 177.93 N).

The results of 2 (knee position angle) x 3 (load intensity) ANOVA for meniscal marker displacement produced no significant position x load interaction $[F(2,14) = 0.307, p = 0.741]$, nor significant main effects for load $[F(2,14) = 2.542, p = 0.114]$ or position $[F(1,7) = 0.324, p = 0.587]$, suggesting that any one combination of position and load were not superior for influencing the extent of meniscal marker displacement in this comparison.

Femoral Marker Displacement
The femoral marker demonstrated significant displacement in an anterior direction relative to the

<table>
<thead>
<tr>
<th>Condition</th>
<th>Knee Position (deg)</th>
<th>Displacement Force (N)</th>
<th>Mean (mm)</th>
<th>STD</th>
<th>95%CI</th>
<th>Meniscus on Tibia</th>
<th>Tibia on Femur</th>
<th>Meniscus on Femur</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>0</td>
<td>0º Pos</td>
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<td>4.5</td>
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<td>4.57</td>
<td>16.27</td>
<td>-6.71, 15.85</td>
</tr>
<tr>
<td></td>
<td>44.48º Pos</td>
<td>2.67</td>
<td>4.46</td>
<td>-0.42, 5.76</td>
<td>6.87</td>
<td>16.47</td>
<td>-4.54, 18.28</td>
<td>-4.20</td>
</tr>
<tr>
<td></td>
<td>44.48º Displ</td>
<td>0.06</td>
<td>0.29</td>
<td>-1.14, 0.26</td>
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<td>1.75</td>
<td>1.09, 3.51</td>
<td>-2.24</td>
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<tr>
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<td>0</td>
<td>0º Pos</td>
<td>2.54</td>
<td>4.51</td>
<td>-0.59, 5.74</td>
<td>5.7</td>
<td>16.19</td>
<td>-5.52, 16.92</td>
</tr>
<tr>
<td></td>
<td>88.96º Pos</td>
<td>2.8</td>
<td>4.25</td>
<td>-0.14, 5.74</td>
<td>9.28</td>
<td>16.29</td>
<td>-2.01, 20.57</td>
<td>-6.48</td>
</tr>
<tr>
<td></td>
<td>88.96º Displ</td>
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<td>0.48</td>
<td>-0.07, 0.59</td>
<td>3.58</td>
<td>1.66</td>
<td>2.43, 4.73</td>
<td>-3.32</td>
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<tr>
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<td>0º Pos</td>
<td>2.47</td>
<td>4.46</td>
<td>-0.62, 5.56</td>
<td>4.45</td>
<td>16.65</td>
<td>-7.09, 15.99</td>
</tr>
<tr>
<td></td>
<td>177.93º Pos</td>
<td>2.88</td>
<td>4.3</td>
<td>-0.10, 5.86</td>
<td>10.61</td>
<td>16.67</td>
<td>-0.94, 22.16</td>
<td>-7.73</td>
</tr>
<tr>
<td></td>
<td>177.93º Displ</td>
<td>0.41</td>
<td>0.35</td>
<td>0.17, 0.65</td>
<td>6.17</td>
<td>2.49</td>
<td>4.44, 7.9</td>
<td>-5.76</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>0º Pos</td>
<td>2.15</td>
<td>4.82</td>
<td>-1.19, 5.49</td>
<td>-2.00</td>
<td>14.49</td>
<td>-12.04, 8.04</td>
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<tr>
<td></td>
<td>44.48º Pos</td>
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<td>4.69</td>
<td>-0.82, 5.68</td>
<td>0.26</td>
<td>14.79</td>
<td>-9.99, 10.51</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>44.48º Displ</td>
<td>0.28</td>
<td>0.38</td>
<td>0.02, 0.54</td>
<td>2.26</td>
<td>0.82</td>
<td>1.69, 2.83</td>
<td>-1.98</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>0º Pos</td>
<td>2.3</td>
<td>4.7</td>
<td>-0.96, 5.56</td>
<td>-1.50</td>
<td>16.25</td>
<td>-12.76, 9.76</td>
</tr>
<tr>
<td></td>
<td>88.96º Pos</td>
<td>2.64</td>
<td>4.34</td>
<td>-0.37, 5.56</td>
<td>2.50</td>
<td>16.16</td>
<td>-8.95, 13.45</td>
<td>0.39</td>
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<tr>
<td></td>
<td>88.96º Displ</td>
<td>0.34</td>
<td>0.65</td>
<td>-0.11, 0.79</td>
<td>3.75</td>
<td>2.75</td>
<td>1.85, 2.83</td>
<td>-3.41</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0º Pos</td>
<td>2.25</td>
<td>4.74</td>
<td>-1.04, 5.54</td>
<td>-1.30</td>
<td>13.2</td>
<td>-10.44, 7.84</td>
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<tr>
<td></td>
<td>177.93º Pos</td>
<td>2.79</td>
<td>4.2</td>
<td>-0.12, 5.70</td>
<td>5.78</td>
<td>13.85</td>
<td>-3.82, 15.38</td>
<td>-2.99</td>
</tr>
<tr>
<td></td>
<td>177.93º Displ</td>
<td>0.54</td>
<td>0.73</td>
<td>0.03, 1.05</td>
<td>7.08</td>
<td>2.84</td>
<td>5.11, 9.05</td>
<td>-6.54</td>
</tr>
</tbody>
</table>
tibial axis during all conditions in response to the posterior tibial mobilization (Table 1, Table 2, Figure 4). This supports the hypothesis of significant tibial displacement in relationship to the femur during this mobilization. The 2 (knee position angle) x 3 (load intensity) ANOVA produced no significant position x load interaction \([F (2,14) = 0.720; p = 0.504]\) nor a significant main effect for position \([F (1,7) = 1.429; p = 0.271]\). However, a significant main effect for load \([F (2,14) = 77.994; p < 0.001]\) was found. Post-hoc pairwise comparison findings suggest that femoral marker displacement significantly increased with each increase in load, irrespective of knee position angle (Table 3). The 177.93 N load produced a significantly greater femoral marker displacement versus the 88.96 N \((p < 0.001)\) and 44.48 N \((p < 0.001)\) loads. Moreover, the 88.96 N load produced a significantly greater femoral marker displacement versus the 44.48 N \((p = 0.03)\) load.

### Meniscal-Femoral Marker Displacement

The meniscal-femoral marker displacement represented the displacement of the meniscal marker with respect to the femoral marker. There was a significant posterior movement of the meniscal marker with respect to the femoral marker (Table 1, Table 2, Figure 4). This does not support the hypothesis of insignificant movement of the MMAH relative to the femur. The 2 (knee position angle) x 3 (load intensity) ANOVA produced no significant position x load interaction \([F (2,14) = 1.192; p = 0.333]\) nor a significant main effect for position \([F (1,7) = 1.042; p = 0.341]\). However, a significant main effect for load \([F (2,14) = 83.620; p < 0.001]\) was found. Post-hoc pairwise comparison findings suggest that the meniscal-femoral marker displacement significantly increased with each increased load, irrespective of knee position angle across the majority of conditions (Table 3). Moreover, the 177.93 N load produced a significantly

### Table 2. Dependent t-tests for meniscus displacement relative to the tibial axis. 1 = Meniscal Marker Displacement with respect to the tibial axis. 2 = Femoral Marker Displacement with respect to tibial axis. 3 = Meniscal minus Femoral Marker Displacement with respect to tibial axis. *sig (2-tailed) at \(p = 0.05\). N = Newton, deg = Degree.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Load</th>
<th>Meniscus on Tibia 2</th>
<th>Tibia on Femur 2</th>
<th>Meniscus on Femur 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t</td>
<td>df</td>
<td>Signif*</td>
<td>t</td>
</tr>
<tr>
<td>1</td>
<td>0deg 0N-0deg 44.48N</td>
<td>-0.619</td>
<td>7</td>
<td>.555</td>
</tr>
<tr>
<td>2</td>
<td>0deg 0N-0deg 88.96N</td>
<td>-1.533</td>
<td>7</td>
<td>.169</td>
</tr>
<tr>
<td>3</td>
<td>0deg 0N-0deg 177.93N</td>
<td>-3.299</td>
<td>7</td>
<td>.013*</td>
</tr>
<tr>
<td>4</td>
<td>0deg 0N-25deg 44.48N</td>
<td>-2.166</td>
<td>7</td>
<td>.072</td>
</tr>
<tr>
<td>5</td>
<td>0deg 0N-25deg 88.96N</td>
<td>-1.477</td>
<td>7</td>
<td>.183</td>
</tr>
<tr>
<td>6</td>
<td>0deg 0N-25deg 177.93N</td>
<td>-2.084</td>
<td>7</td>
<td>.076</td>
</tr>
</tbody>
</table>

### Figure 4. Mean Marker Displacement across all conditions where the femoral marker (Fem Displ) and meniscal–femoral marker (Men-Fem Displ) represents mean displacement (and 95% CI) with respect to the tibial shaft, in mm. The tibial angle displacement (Tib Angle Displ) is represented in degrees.
greater meniscal-femoral marker displacement versus the 88.96 N (p < .001) and 44.48 N (p < 0.001) loads.

**Tibial Angle**

Under each applied load, the tibial angle significantly moved into more knee extension (mean = -2.07 degrees, SD = 0.33) (Figure 4). The 2 (knee position angle) x 3 (load intensity) repeated measures ANOVA produced a significant main effect for tibial angle [F (5,35) = 17.83, p < 0.001]. The pairwise comparisons showed significant angular displacement of the tibia into extension, when the load intensity was greater regardless of the position of the knee (Table 4). Although non-significant, the other pairwise comparisons demonstrated the same trend of greater movement with greater force regardless of position of the knee. When the load intensity was equal, greater angular displacement occurred at 25 deg versus 0 deg knee position angle, except for a load intensity of 44.48 N.

<table>
<thead>
<tr>
<th>Condition (I)</th>
<th>Condition (J)</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Signif*</th>
<th>95% Confidence Interval for Difference</th>
<th>Std. Error</th>
<th>Signif*</th>
<th>95% Confidence Interval for Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>-1.34</td>
<td>0.42</td>
<td>.23</td>
<td>-3.16 - 0.49</td>
<td>0.30</td>
<td>.12</td>
<td>-0.20 - 2.40</td>
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<td></td>
<td>3</td>
<td>-4.14*</td>
<td>0.44</td>
<td>&lt;.001*</td>
<td>-6.06 - 2.22</td>
<td>0.40</td>
<td>&lt;.001*</td>
<td>2.02 - 5.52</td>
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<tr>
<td></td>
<td>4</td>
<td>0.12</td>
<td>0.59</td>
<td>1.00</td>
<td>-2.44 - 2.67</td>
<td>0.53</td>
<td>1.00</td>
<td>-2.58 - 2.00</td>
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<tr>
<td></td>
<td>5</td>
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<td>0.64</td>
<td>.62</td>
<td>-4.35 - 1.18</td>
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<td>.51</td>
<td>-0.88 - 3.57</td>
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<tr>
<td></td>
<td>6</td>
<td>-5.30*</td>
<td>0.80</td>
<td>.01*</td>
<td>-8.80 - 1.76</td>
<td>0.72</td>
<td>&lt;.001*</td>
<td>1.76 - 8.04</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-2.80*</td>
<td>0.48</td>
<td>&lt;.01*</td>
<td>-4.90 - 2.71</td>
<td>0.44</td>
<td>0.01*</td>
<td>0.77 - 4.56</td>
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<td>4</td>
<td>1.45</td>
<td>0.38</td>
<td>.10</td>
<td>-0.22 - 3.13</td>
<td>0.37</td>
<td>.10</td>
<td>-2.98 - 2.08</td>
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<tr>
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<td>5</td>
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<td>0.52</td>
<td>1.00</td>
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<td>0.45</td>
<td>1.00</td>
<td>-1.72 - 2.20</td>
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<td>-3.97*</td>
<td>0.67</td>
<td>.01*</td>
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<td>0.66</td>
<td>.01*</td>
<td>0.92 - 6.68</td>
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<td>4.26*</td>
<td>0.71</td>
<td>&lt;.01*</td>
<td>1.18 - 7.33</td>
<td>0.71</td>
<td>&lt;.01*</td>
<td>-7.16 - 0.95</td>
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<tr>
<td></td>
<td>5</td>
<td>2.55*</td>
<td>0.40</td>
<td>&lt;.01*</td>
<td>0.80 - 4.30</td>
<td>0.31</td>
<td>&lt;.001*</td>
<td>-3.76 - 1.08</td>
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<td>6</td>
<td>-1.17</td>
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<td>1.00</td>
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<td>0.74</td>
<td>.03*</td>
<td>0.32 - 6.79</td>
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</table>

*Table 3. Post-hoc pairwise comparisons for femoral marker displacements with respect to tibia and meniscus. 1 = Femoral Marker Displacement with respect to tibial axis. 2 = Mensical minus Femoral Marker Displacement with respect to tibial axis. *sig (2-tailed) at p = 0.05

<table>
<thead>
<tr>
<th>Condition (I)</th>
<th>Condition (J)</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Signif*</th>
<th>95% Confidence Interval for Difference</th>
<th>Std. Error</th>
<th>Signif*</th>
<th>95% Confidence Interval for Difference</th>
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*Table 4. Post-hoc pairwise comparisons for tibial angular displacement. *sig at p = 0.01. Based on estimated marginal means using Bonferroni adjustment.*
DISCUSSION
Anterior knee pain provoked during end-range passive knee extension may be related to a meniscal movement restriction and increased meniscal load during function. One method of treatment involves the use of manual posterior mobilization of the tibia to specifically target the meniscotibial interface of the knee joint. The results of the current study demonstrated significant meniscus marker displacement relative to the tibial axis during posterior tibial mobilization occurred at a position of 0 deg and under a force of 177.93 N. This finding suggests that posterior tibial mobilization may only be effective in moving the meniscus on the tibia at end-range of knee extension, where maximum congruency of the joint is achieved. Moreover, while such an in situ experiment cannot account for the role of pain or reactive muscular contraction during meniscotibial mobilization execution, the findings suggest that a substantial force may be required to achieve significant meniscotibial movement, encouraging clinicians to be less timid with mobilization forces during this specific application. This required force may be related to the amount of movement allowed between the meniscus and femur that is supported by these findings. Had the meniscus not moved on the femur during the technique in response to congruency between femoral condyle and meniscus, less force may have been required to create the same movement between meniscus and tibia as observed in this study. Thus, it appears that a modest amount of movement was allowed between the meniscus and femur, where the third hypothesis could not be supported. Yet, the femur appeared to serve as a buttress that limited further accompaniment of the meniscus with the tibia as the tibia was pushed posteriorly. Increased force was required to create the anterior meniscal displacement on the tibia, and primarily occurred in the fully extended position.

The findings of the present study support the use of posterior tibial glide mobilization to produce meniscal movement. Although the menisci do not move extensively, due to their anchors at the anterior horn and periphery, such meniscal motion is important for normal knee function. During in vivo studies, investigators observed that both menisci translate anteriorly with knee extension, where the anterior horns move more than the posterior horns. Selected authors examined meniscal movement in vivo in healthy volunteers using MRI. Vedi et al found that the MMAH moved 0.54 cm and the posterior horn 0.38 cm while the lateral meniscus anterior horn moved 0.63 cm and the posterior horn 0.40 cm during unloaded knee motion from 90° flexion to full extension. Kawahara et al examined meniscal movement during unloaded knee flexion. They report a posterior movement of the MMAH of 0.88 cm and posterior horn of 0.56 cm from 0° of flexion to 45° of flexion. From 45° of flexion to 90° of flexion the MMAH moved 1.16 cm and the posterior horn 0.64 cm in posterior direction.

When comparing such in vivo meniscal movement to the present paper’s in situ movement, explored differences appear to be rather large. However, one should keep in mind that the reported in vivo values reflect meniscus movement throughout the entire rotatory flexion-to-extension range from 0° to 90° flexion while the present data reflects MMAH movement during a translatory passive tibial translation while the femur remains stationary. Thus, it is not surprising that MMAH movement during such passive posterior tibial mobilization technique in 0 degrees flexion with a mobilization force of 177.93N applied from the clinician did not result in a comparable movement range versus in vivo. This suggests that a better alternative for examining meniscal response to tibial mobilization should be conducted in vivo. However, cadaveric studies can provide valuable preliminary information to generate legitimacy for subsequent clinical trials. Accordingly, it was this paper’s intent to gain a first insight into the feasibility of meniscal mobilization using an orthopedic manual therapy technique designed to encourage meniscal movement in the meniscotibial interface. Furthermore, the present study aimed to substantiate the existing internal evidence regarding the meniscal mobilization construct by establishing preliminary data. Therefore, inferences about whether 0.41mm MMAH movement is clinically meaningful for patients with MMAH impingement cannot be drawn from this study, thus inspiring future evaluations to address this question.

The authors of this study chose to test the joint in both 0 degrees and 25 degrees of flexion so to assess
the meniscal behaviors both within and outside of the knee’s screw home mechanism\textsuperscript{17,18} and found that the mensicotibial response to posterior tibial mobilization was more profound at the 0-degree position where the joint is more congruent. In light of multiple soft tissue attachments to bone, the menisci dynamically guide and constrain joint motion throughout the available range.\textsuperscript{17,31} This function works with joint architecture to create joint congruency, stability, cartilage protection, and meniscal self-preservation.\textsuperscript{20,33} Medial-lateral joint surface asymmetry further constrains the movement toward the end of knee extension, where the screw-home mechanism creates greater joint congruency and forces lateral tibial rotation.\textsuperscript{17,18} These architectural features collaborate with the cruciate ligaments to influence anterior meniscal movement and contribute to constraining further extension.\textsuperscript{18,19,34} Thus, the present findings were no surprise, considering the change in joint congruency during end-range knee extension.

The current study’s findings suggest that posterior tibial mobilization could influence MMAH translation on the tibia. Meniscal movement limits can emerge in response to inflammation and subsequent adhesive responses.\textsuperscript{15} As the knee approaches full extension, restrictions of meniscal movement may block the normal joint arthrokinematics.\textsuperscript{15} This movement constraint may lead to MMAH compression, resulting in knee extension limits and possible atypical anterior knee pain.\textsuperscript{12} Additionally, meniscal injury can change knee movement mechanics and loading patterns, thus stressing articular cartilage.\textsuperscript{35-38} Such changes can lead to further meniscal problems. Investigators have observed significant changes in the anterior posterior meniscal movements related to architectural abnormalities that accompany knee joint pathology.\textsuperscript{30,38} Using a posterior tibial mobilization in terminal extension may be important for restoring appropriate movement of the meniscus on the femur (meniscofemoral interface) and tibia (mensicotibial interface).

Orthopedic manual therapy can be used to restore motion to a hypomobile joint.\textsuperscript{15,21} Mobilizations that stretch the soft tissues in a resting position or at the point of restriction (Grade III – IV mobilization) can be used to restore tibiofemoral, mensicotibial, and meniscofemoral arthrokinematics to gain optimal joint motion, restore appropriate loading patterns, and achieve the highest level of function.\textsuperscript{14,21} In order to achieve a movement response in the meniscotibial interface, the present findings suggest that a substantial force (177.93 N) may be necessary to create the desired meniscotibial movement response in terminal extension. As a result, clinicians may be less timid with this specific technique and incorporate an appreciable force during posterior tibial mobilization in a knee with an intact posterior cruciate ligament, while continuing to respect a patient’s pain response.

One could argue that a lack of significant mensicotibial displacement in conditions other than 0 deg and 177.93 N in the current study could be related to other architectural constraints in the knee that would limit total knee motion. However, one would then expect similar patterns in the results of meniscofemoral and or tibiofemoral displacements during the different conditions of the mobilization. The results show that this was not the case. First, the femoral marker significantly changed position relative to the tibial marker during all conditions, representing a significant tibial displacement relative to the femur. Moreover, the positive displacement values indicate the femur remained anterior to the tibial axis during a posterior load to the tibia. Because this is the first study to the authors’ knowledge that examined meniscal movement on tibia during tibial mobilization, future research should examine the same phenomena in vivo to further elucidate this conjecture. Moreover, similar in vivo experimentation should examine clinical effects on those patients suspected of experiencing anterior knee pain related to anterior meniscal involvement in the condition.

The meniscal-femoral marker displacement differences were significant between the meniscus and the femur. Pairwise comparisons on the meniscal-femoral marker displacement ANOVA indicate more displacement at a greater load regardless of the position of the knee. This may be influenced by the fact that the femur displacement relative to the tibia was significant and the displacement of the meniscus relative to the tibia was essentially non-significant. This further suggests that the relative immobility of the meniscotibial interface resulted in the meniscus displacing with the tibia on the femur when the mobilizing force was applied.
The tibial angular movement, although small, was statistically significant suggesting that the movement produced during the current load x position conditions was not purely translatory, but under the applied loads the tibia moved into more extension. The authors decided to standardize and control the knee pre-position using the previously described rod through the tibia. Although a small amount of angular extension movement occurred in the tibia during posterior tibial mobilization, this configuration appears to support the anterior meniscal translation. Future research should examine the same parameters while allowing the distal tibia to translate in the same direction as the proximal region during the mobilization.

LIMITATIONS AND FUTURE RESEARCH
There are potential limitations of this study. The use of unembalmed cadaveric specimens, dissection, and subsequent mechanical fixation may not represent full in vivo response to posterior tibial mobilization. However, despite the mechanical fixation, significant movement in the tibiofemoral interface occurred, suggesting that sufficient movement did occur at the joint level. While cadaveric tissues do not fully represent living tissue dynamics with all the dynamic constraints that could accompany that use, the study introduces the potential meniscal movement that responds to a current OMT strategy. Future in vivo experimentation will provide further understanding of meniscal response to mobilization forces.

Specimen preparation included cutaneous and subcutaneous tissue removal, which may have changed the meniscal movement parameters of the specimens. However, all perceived important passive constraints were left intact, including the joint capsule, ligaments and retinacula. Considering the capsule’s connection to the meniscus, one can be confident that meniscal movement parameters did not appreciably change. Future in vivo research will examine these test conditions with cutaneous and subcutaneous tissues intact, further addressing this concern.

The power level for the meniscal position t-test non-significant findings ranged from 11% to 73%. The lowest power test of 11% would have required 84 specimens to achieve a power of 80%. Although more specimens may have increased the power of selected tests, the number of specimens needed to achieve 80% power for all tests was prohibitive for a cadaveric study.

This paper does not examine the role of the present mobilization on managing patients with anterior knee pain provoked with end-range passive knee extension. Orthopedic manual therapy techniques are commonly used to address knee pain and limitations. Authors propose using OMT to address meniscal movement in the meniscotibial and/or meniscofemoral knee joint compartments. However, no evidence has yet to report the effects of these strategies on managing anterior knee pain provoked by end-range passive knee extension. The effect of such mobilization on cadaveric meniscal movement is a prerequisite to understanding the link between OMT to the meniscus (as in our study) and pain relief in this population. Based on our discoveries, future in vivo study replication using MRI should follow. Once confirmed, then a clinical trial examining the effects of the presently described mobilization on anterior knee pain and meniscal movement during end-range passive knee extension should be carried out.

CONCLUSIONS
To the authors’ knowledge, this is the first study to examine movement of specific structures during a manually applied joint mobilization to the tibia in cadaveric specimens. This method could be used for future studies to investigate tissue response to OMT. Investigation and corroboration for in vivo studies could include magnetic resonance imaging. The findings of this study suggest that posterior tibial mobilization in an end-range extension position using a substantial force may produce MMAH translation in an anterior direction with respect to the tibial plateau. This technique may be most applicable in patients presenting with localized anterior knee pain provoked during passive end-range knee joint extension.

REFERENCES
2. Ikeuchi M, Izumi M, Aso K, et al. Clinical characteristics of pain originating from intra-


ABSTRACT

Background: Evidence suggests that individuals with patellofemoral pain (PFP) may develop patellofemoral joint osteoarthritis (PFJOA). Limited data exist regarding an absolute association between PFP and PFJOA. Understanding this relationship will support the need for early interventions to manage PFP.

Hypothesis/Purpose: This study was conducted to determine if females with PFP have a patella position and cartilage biomarkers similar to individuals with PFJOA. It was hypothesized that females with PFP and excessive patella lateralization would have higher cartilage biomarker levels than controls. It also was hypothesized that a significant association would exist between pain and cartilage biomarker levels in subjects with excessive patella lateralization.

Study Design: Single-occasion, cross-sectional, observational

Methods: Pain was assessed using a 10-cm visual analog scale (VAS) for activity pain over the previous week. Patella offset position (RAB angle) was measured using diagnostic ultrasound. Urine was collected and cartilage biomarkers quantified by analyzing C-telopeptide fragments of type II collagen (uCTX-II). Independent t-tests were used to determine between-group differences for RAB angle and uCTX-II. Bivariate correlations were used to determine associations between VAS and uCTX-II for females with PFP.

Results: Subjects (age range 20 to 30 years) had similar RAB angles (p = 0.21) and uCTX-II (p = 0.91). A significant association only existed between VAS scores and uCTX-II for females with PFP who had a RAB angle > 13° (r = 0.86; p = 0.003). Comparison of uCTX-II in the 25-to-30-year-old females with PFP and excessive patella lateralization in the current study to published normative data showed that this cohort had elevated biomarkers.

Conclusion: These findings support that a certain cohort of individuals with PFP have features similar to individuals with confirmed PFJOA (patella lateralization and elevated biomarkers). Additional studies are needed to determine if interventions can reverse not only pain but biomarker levels.

Keywords: Knee; patella; ultrasound imaging

Level of Evidence: 2b (diagnosis)
INTRODUCTION

Patellofemoral pain (PFP) is one of the most common knee conditions experienced by young, active females.\(^1\) Although thought to be a self-limiting problem, emerging evidence supports an association between PFP in early adulthood and patellofemoral joint osteoarthritis (PFJOA) onset later in life.\(^2-5\) PFJOA features include a laterally-positioned patella, patellofemoral joint space narrowing, and elevated cartilage biomarker levels.\(^2,6-9\) Moreover, individuals with PFP have increased patellofemoral joint stress profiles (e.g., elevated bone water content, increased hydrostatic pressure, decreased patellar cartilage thickness, elevated bone metabolic activity) that may lead to degenerative joint changes.\(^10-13\)

Degenerative changes oftentimes are not diagnosed until joint damage is evident on imaging.\(^14\) More concerning is that these changes may occur over 20 years prior to an individual becoming symptomatic.\(^15\) This trend supports the use of biomarkers to identify early osteoarthritic changes and joint damage.\(^8,16\) C-telopeptide fragments of type II collagen (CTX-II) represents a cartilage biomarker typically used to monitor knee joint damage and pain and is easily collected via a urine sample (uCTX-II).\(^6,7,16,17\) Determining if young, adult females with PFP have elevated levels of uCTX-II will provide additional evidence for an association between PFP and PFJOA.\(^18\)

PFP is a multi-factorial problem, which has led to classification schemes to direct treatment.\(^19\) One treatment category is patella malalignment, described as increased patella lateralization within the femoral trochlea.\(^19\) Increased patella stress occurs as patellofemoral joint reaction forces are directed more to the lateral patella facet, a pattern that can adversely affect articular cartilage.\(^9\) A subset of individuals with PFP have patella malalignment, a similar feature associated with PFJOA,\(^5\) that may lead to pain and elevated uCTX-II (Figure 1).

Researchers recommend quantifying patella alignment using radiographs, computed tomography, or magnetic resonance imaging.\(^19\) Limitations with these techniques include excessive cost, limited availability, and/or unnecessary radiation exposure. Alternatively, clinicians may use diagnostic ultrasound (US), a cost-efficient, safe, and readily available imaging tool conducive for a clinical setting.\(^20\) Anillo et al\(^21\) are the only ones to assess patella alignment with US. They measured a patella offset angle (RAB angle); a 13° or higher RAB angle represented excessive patella lateralization. US may represent a viable imaging modality that clinicians can use to identify patients with patella lateralization.

A certain cohort of individuals with PFP may have excessive patella lateralization and elevated uCTX-II levels. Early detection of uCTX-II may allow for early implementation of interventions designed to address impairments to prevent and/or slow disease progression.\(^5,18,22\) The purpose of this study was to determine if females with PFP have a patella position and cartilage biomarkers similar to individuals with PFJOA. It was hypothesized that 1) those with PFP would have higher uCTX-II levels and RAB angles than controls and 2) a moderate-to-good correlation (\(r > .50\)) would exist between pain and uCTX-II in subjects with PFP and a RAB angle > 13°.
METHODS

Study Design
A single-occasion, cross-sectional study design was used. The independent measure was group (females with PFP and controls). Dependent measures were self-reported pain, patella position, and cartilage biomarker levels.

Subjects
Eighteen healthy, recreationally active females with PFP (average age 24.7 ± 3.4 y) and 12 controls (average age 24.3 ± 1.1 y) participated. Males were excluded because of the higher prevalence of PFP in females\(^1,2,3\) and naturally-occurring sex differences in uCTX-II levels.\(^4\) A sample of convenience was recruited from a local university setting. Inclusion and exclusion criteria for subjects with PFP were based on prior investigations (Table 1).\(^2,3\) The most affected extremity was tested for subjects with PFP (six subjects reported bilateral symptoms).\(^5\) Controls participated if they were recreationally active (e.g., exercised at least 30 min, three days a week over the prior six months), had no history of PFP, and met none of the exclusion criteria (Table 1). The right lower extremity was tested for controls.\(^6\) The investigators explained the benefits and risks of this study to all participants. The University’s Institutional Review Board approved the study protocol; all subjects signed an approved informed consent document prior to participation.

Pain Assessment
Pain was assessed using a 10-cm VAS. The extreme left side of the VAS stated “no pain” whereas the extreme right side stated “worse pain imaginable.” Subjects drew a perpendicular line on the scale at the position that best described their pain during activity over the previous week. The distance from the left side (e.g. no pain) of the VAS to the vertical mark made by the subject was measured to the nearest 1/10th of a centimeter and used for statistical analysis. The VAS for pain during activity over the prior week has represented a reliable, responsive, and valid instrument for assessing pain in individuals with PFP.\(^7\)

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<th>Table 1. Inclusion and exclusion criteria for females with patellofemoral pain.</th>
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<td>Visual analog rating during activity over the previous week at a minimum of a 3 on a 10-cm visual analog scale</td>
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<td>Insidious onset of symptoms unrelated to trauma for at least four weeks</td>
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<td>Anterior knee pain during at least three of the following:</td>
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<td>- During or after activity</td>
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<td>- Prolonged sitting</td>
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<td>- Stair ascent or descent</td>
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<td>- During squatting</td>
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<td>Pain with palpation of the patellar facets or pain during a step-down from a 20-cm box or double-legged squat</td>
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<td>Recreationally-active (exercise at least 30 minutes a day, three times a week for the prior six months)</td>
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<td><strong>Exclusion Criteria</strong></td>
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<td>Meniscal or other intra-articular pathology</td>
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<td>Cruciate or collateral ligament laxity</td>
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<td>Patellar tendon, iliobial band, or pes anserine tenderness</td>
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<td>Positive patellar apprehension sign</td>
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<td>Evidence of knee effusion</td>
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<td>Hip or lumbar referred pain</td>
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<td>History of recurrent patellar subluxation or dislocation</td>
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<td>History of knee joint surgery</td>
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<td>Pregnancy</td>
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Patella Position

Patella position was quantified using US to measure the RAB angle (Figure 2), a measure similar to a patella offset angle. The RAB angle was formed by drawing a vertical line perpendicular to the lowest aspect of the femoral trochlea and another from the lowest aspect of the femoral trochlea to the center of the inferior pole of the patella. This measure has excellent inter-rater (ICC2,1 = 0.97; SEM = 4.2°) reliability for the two experienced physicians who measured the RAB angle (four subjects for a total of eight knees).

For testing, subjects were positioned in supine with the quadriceps relaxed and the lower extremity in a neutral position. One physician took two measures of the test knee; each examiner was blinded to the subject’s group assignment. All RAB angles were recorded to the nearest 1/10th of a degree; the average of two measures was used for statistical analysis.

uCTX-II Analysis

An early morning, second void urine sample was collected, immediately processed, and stored at -70°C until analysis. An experienced clinical laboratory scientist, who was blinded to group assignment, analyzed all data using a commercially available enzyme-linked immunosorbent assay (ELISA) based on a mouse monoclonal antibody raised against the EKGPDP sequence of human CTX-II (Urine CartiLaps® EIA; Immunodiagnostic Systems; Gaithersburg, MD). CTX-II was corrected for urinary creatinine concentration using the following formula: corrected CTX-II (ng/mmol) = [1000 X Urine CartiLaps (ng/ml)]/ creatinine (mmol/L). uCTX-II levels were log-transformed (ln uCTX-II) to minimize the influence of outliers and used for statistical analysis.

Statistical Analysis

Separate independent student’s t-tests were used to determine differences for age, mass, height, RAB angle, and ln uCTX-II in females with and without PFP. Bivariate correlations were conducted to determine associations between VAS scores and ln uCTX-II for all subjects with PFP. For this purpose, separate bivariate correlations were conducted for all subjects with PFP, those with a RAB angle < 13°, and those with a RAB angle > 13°. Correlation coefficients (r) were interpreted as follows: none less than 0.25; fair between 0.25 and 0.50; moderate-to-good between 0.50 and 0.75; and good-to-excellent over 0.75. All analyses were conducted using SYSTAT 13.0 (Systat Software, Inc., San Jose, CA) at the 0.05 level of significance.
RESULTS

Subjects with and without PFP were similar with respect to age, mass, and height (Table 2). Subjects with PFP had average VAS scores of 3.7 ± 1.7 cm and controls were pain-free. Females with PFP exhibited a 1.8 times greater RAB angle than controls (Table 3). Associations between VAS scores and ln uCTX-II were not significant when analyzing all females with PFP (r = 0.02; p = 0.94) and those with a RAB angle ≤ 13° (r = -0.36; p = 0.35). However, a significant association (r = 0.86; p = 0.003) existed for those with a RAB angle > 13° (Figure 3).

DISCUSSION

The purpose of this study was to determine if females with PFP have a patella position and cartilage biomarkers similar to individuals with PFJOA. It was hypothesized that 1) those with PFP would have higher uCTX-II levels and RAB angles than controls and 2) a moderate-to-good correlation (r > .50) would exist between pain and uCTX-II in subjects with PFP and a RAB angle > 13°.

No significant between-group differences were shown with respect to biomarkers or patella position. However, a good-to-excellent correlation existed between pain and biomarkers for subjects with PFP and excessive patella lateralization.

Patella Position in Females with and without PFP

Although the RAB angle for females with PFP was 1.8 times greater than controls, this difference was not significant. The post-hoc power analysis showed that 65 females with and without PFP were required to attain 80% power. Although the imaging technique had excellent inter-rater measurement reliability, the measure's inherent variability most likely precluded obtaining statistical significance. Additional larger-scale studies are needed to determine if
females with PFP have increased patella lateralization than controls.

Fifty percent of females with PFP exhibited a high RAB angle (18.6° ± 10.9°) while the remaining 50% did not (2.8° ± 3.0°). This pattern suggested that impairments other than static patella position may have existed. Faulty lower extremity kinematics like excessive hip adduction and/or internal rotation during weight bearing activities can increase lateral patellofemoral joint loading and stress. A relative delay in vastus medialis-to-vastus lateralis activation during weight bearing activities also may lead to increased lateral loading and stress. This determination could not be made since kinematic and neuromuscular factors were not assessed.

**Cartilage Biomarker Levels in Females with and without PFP**

Subjects with and without PFP had ln uCTX-II of 5.9 ± 0.8 ng/mmol and 5.9 ± 0.6 ng/mmol, respectively, which exceeded levels reported for individuals with confirmed early knee osteoarthritis. However, comparing the current study findings to Ishijima et al presented limitations because age can affect uCTX-II. Mouritzen et al found naturally-higher non-log-transformed uCTX-II in healthy 20-to-24-year-old females (500 ng/mmol) than 25-to-30-year-old females (225 ng/mmol). uCTX-II continued to be lower in healthy 31-to-35-year-old females (150 ng/mmol). They concluded that the naturally-higher levels of uCTX-II seen in 20-to-24-year-old females resulted from higher bone turnover.

To make meaningful comparisons to Mouritzen et al, data for subjects with PFP were stratified by age (20-to-24 years and 25-to-30 years), expressed as non-log-transformed uCTX-II, and averaged (Figure 4). Average non-log-transformed uCTX-II for the 20-to-24-year-old subjects, regardless of RAB angle, were similar to previously reported values from Mouritzen et al. This finding suggested that these females with PFP had naturally-higher uCTX-II consistent with their age group regardless of patella position.

Meaningful differences existed when making the same comparison for 25-to-30-year-old females. Females in this age range with PFP and a higher RAB angle had non-log-transformed uCTX-II (525.8 ng/mmol) that was 2.2 times higher than healthy, age-matched females (225 ng/mmol). This difference indicated that this subgroup of females with PFP had higher than expected uCTX-II for their age range. Therefore, differences in uCTX-II based on patella position may not necessarily be clinically meaningful until naturally occurring bone turnover ceases. Additional studies are needed to make this determination.

**Associations between Pain and Cartilage Biomarker Levels based on Patella Position**

No significant association was found between VAS and ln uCTX-II when analyzing all females with PFP, regardless of patella position, and those with a RAB angle \( \leq 13° \). However, a good-to-excellent correlation existed for females with PFP classified as having excessive patella lateralization (Figure 3). This finding, plus the fact that these subjects had elevated biomarkers than reported normative data, suggested that at least a cohort of females with PFP had similar features (e.g., patella lateralization and elevated biomarkers) as individuals with confirmed PFJOA.

**Implications for Rehabilitation**

PFP is no longer considered a self-limiting problem but a disease process. Study findings support this belief since 25-to-30-year old females with PFP and excessive patella lateralization had elevated biomarkers, which could suggest cartilage degradation. These results further highlight the importance of early management of females with PFP.
A challenge with the management of PFP is its multifactorial nature and the need for identifying treatment classifications for this patient population. While therapeutic exercise remains the recommended treatment strategy, the addition of patella taping can provide short-term benefit for individuals with PFP and PFJOA. This investigation supports the use of US to identify females with PFP and excessive patella lateralization. This finding may be useful in identifying females with PFP who may benefit from patella taping. However, additional studies are needed to make this determination.

Delimitations
Study findings cannot be extrapolated to males with PFP since only females were examined. Males were excluded because of naturally-lower uCTX-II than healthy, age-matched females, and PFP also is more prevalent in females, and males with PFP may have different impairments.

Another delimitation was the procedure used to measure patella position. Measuring static patella position with subjects in supine and the quadriceps relaxed most likely did not represent functional demands. Some subjects may have demonstrated greater patella lateralization if positioned in either supine or standing with the quadriceps contracted. Pilot testing showed unacceptable measurement reliability when measuring in supine and standing with the quadriceps contracted. Therefore, all subjects with excessive patella lateralization may not have necessarily been identified.

Finally, the current study was a pilot project to examine the interrelationship between patella position and biomarkers. For this reason, only uCTX-II was assessed since it represented the most commonly used biomarker to identify and monitor knee degenerative changes. However, use of a single biomarker probably did not adequately characterize cartilage pathophysiology. Future studies should examine a cluster of cartilage degradation and cartilage synthesis biomarkers in this subject cohort.

Limitations
This study has additional limitations. uCTX-II has been used to identify and monitor knee osteoarthritis. However, it was a byproduct of cartilage degradation that only provided an indirect assessment of joint damage. uCTX-II lacked the ability to distinguish between PFJOA and TFOA. However, PFJOA has been considered a risk factor for not only TFOA onset but progression. Poole et al concluded that individuals with knee OA can undergo degenerative changes over 20 years prior to becoming symptomatic. Biomarkers may provide a way for early detection of degenerative changes and further support the importance of rehabilitation for females with PFP. Radiographs were not taken, precluding the ability to know if subjects with PFP and elevated uCTX-II had cartilage changes to the tibiofemoral, patellofemoral, or both joints. However, inclusion criteria were consistent with prior works intended to exclude subjects with evident degenerative changes. Also, one-third of subjects with PFP had bilateral symptoms and it was unknown if this presentation affected uCTX-II levels. Finally, uCTX-II typically was higher in females between the ages of 20-to-24 years due high bone turnover. Using more sensitive measures of cartilage biomarkers (e.g., serum or synovial fluid samples) may have identified differences in this cohort.

CONCLUSION
This study was the first to compare patella position and cartilage biomarkers in young, adult females with and without PFP. While no significant differences were identified, a clinically-relevant association existed between pain and biomarkers in females with PFP and excessive patella lateralization had higher biomarker levels that exceeded both normative data and values from individuals with confirmed PFJOA. Future studies are needed to determine the effect that an intervention can have on reducing both pain and biomarkers in this cohort of females with PFP.

REFERENCES


ABSTRACT

Background: Despite the increased use of whole body vibration among athletes, there is limited literature on its acute effects within heterogeneous populations such as untrained adults or recreational athletes.

Hypothesis/Purpose: The purpose of this study was to investigate the acute effects of whole body vibration on vertical jump, power, balance, and agility for untrained males and females. It was hypothesized that there would be an effect on each outcome variable.

Study Design: Quasi-experimental, pretest-posttest design.

Methods: Twenty males and sixteen females, mean age 24.5 years, were assessed for vertical jump height and power as measured by the Myotec accelerometer, balance as measured by the NeuroCom Balance Master System, and agility as measured by a modified T-test. Each session consisted of a five-minute treadmill warm-up, a practice test, a baseline measurement, a two-minute rest period, whole body vibration at 2 mm and 30 Hz for 60 seconds, and a final measurement. Three different counterbalanced testing sessions were separated by a minimum of 48 hours in between sessions to minimize fatigue.

Results: Significant differences existed for both genders for main effect of time for Agility (p = 0.022); end point excursion Left (p = 0.007); and maximum endpoint excursion Left (p = 0.039). Differences for main effect of gender revealed females performed better than males in the following respects: end point excursion Right (p = 0.035); and maximum endpoint excursion Left (p = 0.014); maximum endpoint excursion Right (p = 0.024); and maximum endpoint excursion Left (p = 0.005). Males performed better than females in two respects: Agility (p < 0.0005) and Power (p < 0.0005). A significant interaction was observed between time and gender for vertical jump (p = 0.020). Simple main effects revealed males jumped higher than females during both pre and post intervention, p < 0.0005. Females had a significant decrease in the vertical jump post intervention (p = 0.05).

Conclusion: Results indicated that whole body vibration produced significant differences in the main effect of time and agility, and end point and maximum end point excursion Left for both genders, acutely. Females performed better in balance compared to males and poorer in vertical jump, but males performed better in agility and power.

Key Words: Agility, Balance, Jump Height, Power, Whole Body Vibration

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INTRODUCTION

In recent years, there has been an increased interest in the use of whole body vibration (WBV) to increase athletic performance, but also as it relates to untrained adults or recreational athletes.1-7 The potential benefits suggest that WBV could be a practical warm-up before exercise.5,9 Current research is conflicting on whether or not WBV has a significant effect on vertical jump height, power, balance, and agility. Though many studies show improvements after exposure to WBV, some literature shows no improvement in performance following WBV.1,2,4,10-13 The differences in findings may be due to the use of different frequencies (25-50 Hz), amplitudes (2-10 mm), and duration of WBV (30 sec-10 min).

Armstrong et al.10 found that the most appropriate time to assess vertical jump height is within five minutes of WBV, because after that time the effects begin to decrease. Although they found no difference between different frequencies (30, 35, 40 or 50 Hz) and amplitudes (2-4 or 4-6 mm), they did find that the use of WBV causes an increase in vertical jump height in a heterogeneous sample (minimally active students to intercollegiate athletes) of male and female college students. While investigating male and female competitive basketball players, Colson et al. found that a WBV training session in conjunction with a conventional basketball training program resulted in increased knee extensor strength, but no change in countermovement jump height.1 The training program for the experimental group in this study included twelve 20-minute WBV sessions with an amplitude of 4 mm and frequency of 40 Hz. The participants performed trials of bilateral, right leg, and left leg countermovement jumps before and after the intervention, taking off and landing on a force platform, which recorded kinetic data. Pojskic et al. found that WBV was significantly better at improving countermovement jump, 15 meter sprint time, and agility using a T-test in healthy male college football players.4 They concluded that body weight loaded WBV is better at improving these variables over an unloaded preconditioning protocol.

While some of these and many other longitudinal research studies examined highly trained athletes,3,5,14,15 there is limited research on the acute effects of WBV on more heterogeneous populations such as untrained adults or recreational athletes. Therefore, the purpose of this study was to examine the acute effects of WBV on vertical jump, power, balance, and agility for untrained males and females. It was hypothesized that there would be a change in each of the four performance variables following an acute bout of WBV.

METHODS

Participants
Thirty-six untrained male and female adults (age 24.5 years ± 2.2 SD) participated in the study.
Untrained was defined as individuals who are not collegiate or professional athletes. An a-priori power analysis was conducted in order to determine the minimum number of participants necessary to ensure sufficient power. Using a power of 0.8 and a large effect size of 0.4, the minimum number of subjects required was determined to be 26. In order to account for an approximate 15% attrition rate, a total of 36 participants was obtained.

The inclusion criteria consisted of being between 18 and 40 years of age and being able to speak and understand English well enough to comprehend the consent form and instructions. Participants were excluded if they were pregnant, suffered from an orthopedic injury within the prior six months, had severe osteoporosis, a severe heart condition, an acute thrombosis, a pacemaker, or cancer. Each group served as their own control group by performing a pretest before being exposed to WBV.

Confidentiality was maintained through a numbering system. All information was stored on a password-encrypted computer for the duration of the study.

The study was approved through the University Institutional Review Board. All participants gave verbal approval and signed informed consent that explained the risks, benefits, and procedures of the study prior to participation.

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<td>Freq: 50 Hz Amp: 4 mm Duration: 4 sessions within 10 days, 5x60s per session</td>
<td>CMJ (+) 15-m sprint (+) Agility (+)</td>
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Key: (+) = significant improvement; (-) = no significant change; (-)* = decline in performance
Equipment
A Power Plate (Pro5, Performance Health Systems, Northbrook, IL) vibration plate was used in the study. The Pro5 produces a linear vibration and can be set to different amplitudes, frequencies, and durations. Amplitude is the amount of linear displacement caused by the power plate and is measured in millimeters. Frequency is the number of oscillations per unit time and is measured in hertz (sec\(^{-1}\)). Duration is the length of time that the vibration occurs and is measured in seconds. The settings used in this study included an amplitude of 2 mm, a frequency of 30 Hz, and a duration of 60 seconds. This protocol was developed based on other studies that utilized vertical jump, power, balance, and agility variables in their research.\(^{10,16,17}\)

The Myotest (Myotest Pro 2, Myotest SA, Sion, Switzerland) was used to measure vertical jump height and power output. It utilizes an accelerometer to measure jump height, power, force, velocity, and flight time. For males, the Myotest was shown to have an intra-session reliability ICC value of 0.95 and an intersession reliability ICC value of 0.88. For females, the Myotest was shown to have an intra-session reliability ICC value of 0.91 and an intersession reliability ICC value of 0.92.\(^{18}\) The Myotest has been shown to have excellent validity with a Pearson’s product correlation coefficient of \(r = 0.89\) when compared to the gold standard force plate.\(^{19}\) In addition, validity was found to be high in studies utilizing a countermovement jump.\(^{20}\)

In order to measure dynamic balance, the Limits of Stability (LOS) test was used as part of the clinical assessment battery from the NeuroCom Balance Manager system (SMART EquiTest, Natus Medical Incorporated, Pleasanton, CA). The LOS test measures five variables associated with the participant’s displacement of their center of gravity (COG) including reaction time (RT), movement velocity (MVL), end point excursion (EPE), maximum endpoint excursion (MXE), and directional control (DCL). The test consists of eight timed trials in which the participant attempts to move their COG towards one of eight targets located at different points along their theoretical LOS. The LOS test has been found to have good reliability with ICC values of 0.80, 0.88, and 0.69 for MVL, EPE, and DCL respectively.\(^{21}\)

Procedure
A two-way mixed method ANOVA study design was utilized to compare males and females for each of the dependent variables measured: vertical jump height, power, balance, and agility.

Prior to participation in the study, the participants were given an explanation of the study, but were not informed of the hypotheses on whether or not there would be a change in each of the conditions. Participants were required to attend three different testing sessions at the university research laboratory, separated by a minimum of 48 hours between sessions to minimize fatigue and any potential cumulating effects of the WBV. Each session was dedicated to the measurement of one of the dependent variables: vertical jump height, power, balance, or agility; vertical jump height and power were measured at the same time using the Myotest. The order in which subjects performed each of these tests was randomized using a counterbalanced design (random order with rotation) Figure 1.

During each session, participants began with a five-minute warm-up on a treadmill, which was set to the participant’s preferred walking speed. Immediately following the warm-up, a practice test of the dependent variable being measured was recorded to
account for any learning effects. Participants then had a two-minute rest period before a second baseline measurement was collected. After a two-minute rest period, subjects underwent the WBV intervention at 30 Hz, 2 mm for 60 seconds in a semi-squat position at approximately 60 degrees of knee flexion. A final measurement of the dependent variable was collected immediately after the intervention. For the vertical jump pre- and post-tests, participants jumped three times and an average was taken. The pre- and post-tests for balance were performed once to minimize the possibility of the acute WBV effect wearing off as time proceeds. The pre- and post-tests for agility tests were only performed once to minimize the effects of fatigue. The four examiners were second year physical therapy students who underwent training for each testing intervention by a physical therapist who is a Board Certified specialist in sports physical therapy. Three steps were taken to ensure consistency: the same tester was used throughout the duration of the experiment for an individual condition; each condition was assessed by a different investigator to reduce threats to internal validity; prior to commencing the study, all four examiners met during two separate one-hour sessions to discuss and practice techniques.

**Statistical Analyses**

A 2 (group: male, female) × 2 (time: pretest, post-test) mixed method ANOVA was used to determine changes for each of the dependent variables. An alpha level was set at 0.05 and power was set at 0.8 for each variable. Post hoc analysis was performed with pairwise comparisons if significant interactions were found. Statistical analysis was performed using the SPSS, 23.0 statistical software package (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp.).

**RESULTS**

A significant interaction was observed between time and gender for vertical jump as shown in Table 2. Follow-up (simple main effects) independent t-tests revealed a difference between groups for pre-testing, \( t_{1,34} = 8.48, p < 0.0005 \) and post testing, \( t_{1,34} = 8.68, p < 0.0005 \) with males jumping higher than females during pre and post time periods. Using paired t-tests, females had a significant decrease in the vertical jump height post WBV, \( t_{15} = 2.137, p \leq 0.05 \).

Significant outcome measures via a mixed method ANOVA for the main effect of time are shown in Table 3. Differences were observed for males and
females in the following areas: Agility: \( F_{1,34} = 5.77 \); EPE Left: \( F_{1,34} = 8.12 \); and MXE Left: \( F_{1,34} = 4.60 \).

When looking at the main effect of gender, females performed better overall when compared to males in the following balance components as shown in Table 4: EPE Right: \( F_{1,34} = 4.80 \); EPE Left: \( F_{1,34} = 6.67 \); MXE Right: \( F_{1,34} = 5.55 \); and MXE Left: \( F_{1,34} = 9.06 \). Males performed better overall than their female counterparts in the following performance variables: Agility: \( F_{1,34} = 42.16 \) and Power: \( F_{1,34} = 23.82 \).

**DISCUSSION**

The purpose of this study was to investigate the acute effects of WBV on vertical jump, power, balance, and agility for males and females in an untrained adult population. It was hypothesized that there would be an effect on each condition following an acute bout of WBV. Previous research is non-definitive on the possible benefits of WBV in a group of untrained adults or for gender differences.

**Vertical Jump**

Regarding the effects of WBV on vertical jump for males and females, WBV produced no significant effect for males, but caused a decrease in vertical jump height for females. These findings did not coincide with the results of any of the literature reviewed as much of the research literature reveals an increase in jump height as a result of vibration...
training. Cochrane et al. examined the effects of WBV on vertical jump in 24 sports science students (16 males and 8 females) and found no significant differences between the WBV group and the control group. However, Torvinen et al. produced conflicting results, investigating 56 nonathletic volunteers (21 men, 35 women, ages 19-38 years old) and finding a significant increase in countermovement vertical jump height in the WBV group compared to the control group. When examining the effects of WBV on 9 males aged 19-23 years old, Cormie et al. found that countermovement jump height increased following the use of WBV. This is in agreement with Wyon et al. who, when investigating the effects of WBV on 18 undergraduate female dancers, found that vertical jump height improved with the use of WBV.

Although it is difficult to explain why a decrease in jump height for females occurred, it may be due to the untrained nature of the participants. It is also possible that the results seen with the present study could be due to the vibration parameters (frequency, amplitude, duration) used which is variable among studies. Additionally, the change could be due to measurement error; but this is inconclusive, as the SEM for a countermovement vertical jump using the Myotest has not been shown.

Main Effect of Time
Much research has shown that WBV appears to have immediate effects on postural control and static balance, but other research in this area is inconclusive, particularly as it relates to dynamic standing balance. Our results demonstrated improvements in a few components of dynamic standing balance, specifically EPE Left and MXE Left. These findings are consistent with Ritzmann et al. who examined the effects of WBV on 40 subjects (17 female, 23 male, age 25 ± 4 years) and found that balance improved more with the WBV group compared to the control group. However, the results of this study conflicted with a study performed by Pollock et al. who found that, using 18 adults (15 females, 3 males aged 24.3 ± 1.5 years), WBV had no effect on balance. They suggested that healthy young adults may have little margin for improved balance during simple tasks as one possible explanation. Additionally, Ebbon et al. found that WBV may actually impair dynamic stability and balance in collegiate Division One female basketball players. They proposed that the duration of the WBV stimulus in their study (two minutes) may have been too long, leading to overstimulation and fatigue of muscle spindles and a consequent decline in performance. Given the paucity of research in this area, it is difficult to ascertain specifically why improvement in dynamic balance occurred. We can speculate that perhaps effects of WBV caused underlying neural mechanisms to improve coordination, but this speculation is beyond the scope of this research.

Regarding the effects of WBV on agility for males and females, agility times improved after an acute bout of WBV. This agrees with a study by Ghazalian et al., who found an improvement in agility following WBV in a group of 26 healthy male students and Pagaduan et al. who studied the effects of acute WBV on college football players. However, these findings did not coincide with studies performed by Cochrane et al. or Torvinen et al. Both researchers found no significant differences between the WBV and control groups for agility or shuttle run times, respectively. However, it should be noted in the Cochrane study that the performance tests were performed two days after the last WBV training. Although several theories persist in the literature regarding reasons for positive effects of WBV, the findings observed in this study may simply be due to a warm-up effect resulting from intramuscular temperature increases during WBV exercise as noted by Cochrane et al. As such, an acute bout of WBV may have beneficial effects on any activities requiring quick lateral movements.

Main Effect of Gender
As noted, females revealed better dynamic standing balance ability than males for several of the components of dynamic standing balance. These findings reveal that WBV could help to broaden the base of support (BOS) of females. However, these results are in contrast to Ebbon et al., who found that WBV has no effect on and may impair dynamic stability in NCAA Division One women basketball players. The WBV component of this study differs from Ebbon et al. in amplitude (2 mm vs 4 mm),
frequency (a constant 30 Hz vs a variable 30, 40, and 50 Hz) and duration (1 minute vs 2 minutes). Additionally, our test subjects in this study maintained a constant position of slight knee flexion during WBV while Ebben's subjects performed 10-12 body weight squats for 60 seconds of their total WBV treatment time. We may theorize that muscle fatigue from the squats may have contributed to the decline in performance after WBV. Although many of the studies between genders have focused on children and adolescents or the elderly, researchers have reported significant gender differences in balance skills with younger females tending to have higher balance scores than younger males. This changes with elderly males and females as females tend to display greater changes in postural sway with age than males, but evidence is lacking regarding dynamic standing balance ability between young adult and middle-aged males and females.

Differences between males and females were found for agility, power, EPE Right, EPE Left, MXE Right, MXE Left. Overall, males demonstrated faster agility performance times and greater power than females. Although this study examined only agility performance times and not other factors relating to agility such as change of direction (COD) or other agility maneuvers, several researchers have observed that males produce a faster COD as well as overall agility performance than females. Regarding power, these findings are consistent with previous research supporting gender differences for overall anaerobic power output and maximal strength. Much of the literature reveals that power output can be acutely increased by a bout of WBV exercise whether it be from neuromuscular facilitation or a warming-up effect. As such, it appears that WBV did not have any major distinguishing effects on these components for gender.

Limitations
This study has some limitations. The internal motivation of the participants is a potential limitation, as there was no particular incentive for performing at maximal effort. The positioning of the participants during WBV is another limitation. Maintaining the recommended semi-squat position for 60 seconds may have led to muscle fatigue and, therefore, decreased performance. The set of parameters used for amplitude, frequency, and duration of WBV is another limitation. Currently, the evidence is inconclusive regarding the settings for optimal results. Further studies may help determine ideal parameters for WBV. Finally, the results of this study may not be generalizable to populations differing from the study group. This study did not investigate the effects of WBV on improving agility in trained individuals or balance in impaired individuals, but it does raise those questions for future research. However, these findings do suggest that WBV reduces the performance of vertical jump in untrained females.

CONCLUSIONS
The results of this study indicate that a bout of acute WBV is effective for improving agility time and some components of dynamic balance including EPE and MXE in untrained adults. In regard to gender, males demonstrated increased performance in power and agility times. Females performed better in several aspects of dynamic standing balance, which included EPE Left and Right and MXE Left and Right. A significant interaction was found for vertical jump between males and females with females actually decreasing vertical jump performance. Overall, the use of WBV may be beneficial in improving some aspects of athletic performance including balance and agility. Practical application for the combination of improvements in balance and agility may include playing offense and defense in sports such as basketball, soccer, hockey, and football as well as cutting maneuvers in all sports.

REFERENCES


ABSTRACT

Background: Lumbar spine range of motion (ROM) is a key component of injury prevention and normative data has not currently been determined for an elite gymnastics population. In current clinical practice, it is commonplace to measure sagittal spinal alignment, during ‘high-load, low-dynamic’ control tasks, subjectively, while also only considering the lumbar spine as a single segment.

Purpose: To develop normative data for total lumbar spine ROM and ROM during a simulated landing task (SLT) in an elite gymnastics population, evaluating findings in the context of the existing biomechanical literature.

Study Design: Repeated measures, cross sectional design

Methods: Lumbar spine and low lumbar spine (LLS) ROM during a SLT were measured, using the Dorsa Vi: Vi Perform™ system in asymptomatic male and female elite gymnasts. Values for maximal ROM and LLS angle during the SLT were collated and descriptively analyzed. Lumbar ROM and posture was evaluated in relation to the current biomechanical literature and a proposed Conceptual Compressive Lumbar Load Distribution Model (CCLLDM).

Results: Thirty elite gymnasts (15 male, 15 female), participated. Participants were members of the British Artistic Gymnastics elite senior and junior training program and were between the ages of 16 to 30 years. Mean (SD) maximal lumbar spinal movements were 64.23˚ (6.34°) for flexion and 25.89˚ (11.14°) for extension. During the SLT, participants performed lumbar spine flexion of 15.96˚ (8.80°), when considered as a single segment. When considering the lumbar spine as a two segment model the LLS position during the SLT was towards end range anterior pelvic tilt, suggesting LLS extension.

Conclusion: These data provide a baseline for asymptomatic lumbar spine movements in an elite gymnastics population and provides insight into upper and lower lumbar spine movement during a SLT. The data and newly developed CCLLDM provide clinicians with a potential framework to identify sporting skills that may be associated with increased spinal tissue load.

Levels of Evidence: 3b

Keywords: Gymnastics, normative data, range of motion, spinal neutral
INTRODUCTION
Globally, low back pain (LBP) is associated with significant activity modification and individual burden, resulting in more years affected due to disability than any other condition. LBP contributes up to 30% of total reported athletic injuries. This may lead to a loss of training time and ultimately, may impact competitive performance. Time loss injury incidence is influenced by sport specific demands, with the increased risk of LBP in sports with repeated hyper-extension and rotation movements. Gymnasts are at particular risk, with spinal injury prevalence ranging 25-85%. Landing in gymnastics results in significant ground reaction forces, up to 13 times bodyweight and has been linked to spinal tissue pathology. Common sites of spinal injury include the apophyseal joints, intervertebral discs, and the pars interarticularis.

Awareness of total lumbar spine range of motion (ROM) and sagittal alignment are considered key components in the identification, management and rehabilitation of lumbar spine pathology. Gender specific lumbar spine ROM normative data have been published for healthy participants aged 16-90 years, including subjects with varied levels of physical activity. Although these data provide a broad overview of total lumbar spine ROM and highlight the impact of arthrogenic, myogenic and discogenic degeneration on ROM, the heterogeneity of the data provides little insight when extrapolating findings to elite physically active populations. To improve LBP prevention and rehabilitation strategies in an elite gymnastics population, normative data in this physically active subgroup is required.

Although several systems have an ability to measure lumbar spine ROM, limitations exist. Limitations include skin movement errors, variable reliability and validity, and the inability to analyze and collect data wirelessly. X-ray and fluoroscopy are considered the ‘gold standard’ for assessing lumbar spine ROM, however, repeated radiation exposure has documented risks. The Dorsa Vi: Vi Perform™ enables measurement of lumbar sagittal, frontal and transverse planes of movement through wearable wireless accelerometers, and thus during unrestricted functional and sporting activities.

Awareness and reduction of compressive load distribution, maximal and cumulative end range spinal movements, have been proposed to reduce tissue damage and in turn, lumbar spine time loss injuries. In order to optimize the distribution of axial compressive load through spinal structures during a ‘high-load, low-dynamic’ control task such as a gymnastics landing, the principle of neutral spine positioning is advocated. Alternatively, optimal spinal posture has been suggested to be ‘an envelope of motion and loading associated with optimal tissue health (p97)’ or neutral zone of movement away from end range, not a fixed neutral position. Additionally, considering the lumbar spine as a single segment (T12-S2) during functional tasks has been shown to be inadequate and not reflective of full lumbar spine kinematics. In order to assess lumbar spine posture during a ‘high-load, low-dynamic’ controlled gymnastics landing task, the lumbar spine must be considered as a minimum of two segments. Differing contributions of ROM from the upper (T12-L3) and lower (L3-S2) lumbar spine segments have been demonstrated during the activities of sit to stand and drop jump landing. In order to consider the lumbar spine as two segments, low lumbar spine (LLS) maximal movement is driven by anterior and posterior pelvic tilt and parameters for the ‘envelope of motion’ for the LLS must be established.

The evident gap between current clinical practice and existing literature, presents challenges when managing risk and rehabilitating lumbar spine pathology in elite athletes. Limited research has investigated frontal plane postural changes, as movement in this plane rarely occurs in isolation. The sagittal lumbar spine position associated with optimal compressive load distribution is not well defined in the current literature and the neutral spine position is currently guided by clinical subjective opinion. Although an ‘envelope’ of spinal movement has been suggested with regards to optimal compressive lumbar load distribution in vivo, evidence based movement parameters have not been applied to this statement. Currently lumbar spine sagittal alignment and the parameters to the ‘envelope of motion and loading’ are considered independently and require a synergistic approach.
Therefore a new model, The Conceptual Compressive Lumbar Load Distribution Model (CCLLDM) (Figure 1) is presented. This model provides evidence based parameters to describe the ‘envelope of motion’ and establishes an optimum spinal posture, determined by axial compressive load distribution.

The model presented is structured around a zone of sagittal spine alignment associated with optimal load distribution (ZOLD), defined as even axial load distribution through the anterior and posterior lumbar spinal segment. The authors’ hypothesize the ZOLD is between 0-2˚ of flexion per segment level.

A reduced degree of segmental flexion results in increased load cycles tolerated by spinal tissue before failure. The maximal lumbar flexion parameter is defined as 80% of maximal flexion range, as this position has been shown to optimally tension the lumbo-dorsal fascia, reducing peak intervertebral disc and ligament load exposure. Spinal segment extension results in increased posterior neural arch loading as the disc is stress shielded. Capsular ligament loading occurs at 4˚ of extension per segment level, which combined with increased extensor muscle activation, may be linked to myogenic fatigue. Therefore erect standing sagittal alignment, shown to increase lumbar lordosis by 2˚ of extension per segment level, is defined as the extension parameter limit.

Currently no normative data exists regarding total and lumbar spine movement during a SLT, associated with high ground reaction forces, in an elite gymnastics population. The neutral spine position is determined subjectively and considered independently to the ‘envelope of motion’ associated with optimal tissue health. The primary purpose of this study was to develop normative data of total lumbar spine ROM, and total LLS ROM during a SLT in an elite gymnastics population. The secondary goal was to evaluate the findings in the context of the proposed CCLLDM.

METHODS

Design
A repeated measures, cross sectional study was conducted in a sample of 30 asymptomatic, world class and professional, elite gymnasts. Data collection was completed, in performance gymnasium by an experienced sports physiotherapist. Data were collected over nine days between training sessions.

Sample
Thirty elite gymnasts (15 male, 15 female), were approached and consented to participate. Participants were members of the British Artistic Gymnastics elite senior and junior training program and...
were between the ages of 16 to 30 years. Participants were excluded if they had a previous history of spinal surgery, lower limb pathology preventing study protocol completion, were pregnant or less than six months post-partum, had inflammatory or neurological conditions, undiagnosed pain conditions, implanted electronic devices or a current or previous (within the prior six months) episode of back pain, resulting in a time loss injury, which was defined as missing a scheduled session.24

Ethics statement
All participants were provided with a Participant Information Sheet detailing the study purpose, participation requirements, and right to withdraw. All participants provided written informed consent. Participants aged <18 years old were required to have a parent/guardian co-sign the consent form.25 Permission to access the elite gymnastics population was afforded by British Gymnastics and the English Institute of Sport. Ethical approval was obtained from the University of Birmingham (Ref: 24_02_15_SW).

Apparatus
The Dorsa Vi: Vi Perform™ (dorsaVi, Docklands, Victoria, Australia) measurement system consists of an upper and lower sensor with two tri-axial accelerometers and two single axis gyroscopes. It was placed on the skin using latex free, disposable adhesive application as per the system protocol.9,26 The reader is directed to Ronichi et al9 and Charry et al26 for further information reading the Dorsa Vi: Vi Perform™ system protocol. The Dorsa Vi system has previously demonstrated excellent inter- and intra-tester reliability for lumbar flexion (ICC 2.1; 95% CI 0.86 inter-tester, 0.86 intra-tester) and lumbar extension (ICC 2.1; 95% CI 0.91 inter-tester, 0.79 intra-tester).27 The use of the Dorsa Vi: Vi Perform™ was therefore supported for use by a single rater in this study.

Procedure:
Participants were required to have risen from bed > three hours prior to participation, to ensure resolution of morning stiffness.28 Height and weight were measured as part of the the Dorsa Vi: Vi Perform™ system protocol. Participants were instructed to stand with feet shoulder width apart with shoulders flexed to horizontal in the sagittal plane. A visual target was placed 1.5 meters away to standardize head posture, as downward gaze during a squat has been shown to increase hip and trunk flexion.29 To complete the SLT (due to reduced apparatus accuracy at speed) participants were asked to squat to a position of 90˚ knee flexion17 to simulate soft landing technique, associated with reduced peak ground reaction force.30 A hand held goniometer was used to measure knee flexion by the lead author, following a standardized protocol.31 This method has demonstrated high intra-tester reliability (ICC 0.85-0.99) and high validity (ICC 0.98-0.99).31 A height adjustable fitness aerobic step was used as a reference point for SLT repetitions in order to standardize depth. To ensure participants did not sit on the aerobic step, defined by Akerblom32 as weight bearing through the ischial tuberosities, a set of electronic scales were placed on the step. During the performance of the SLT participants were instructed to make contact with the electronic scales to an upper limit of 20% of sitting body weight. Participants then completed a standardized warm up of five movements into end range lumbar flexion and extension, anterior and posterior pelvic tilt21,33 to avoid serial effects11 and stabilize mobility performance.34

The Dorsa Vi: Vi Perform™ system was placed on the participants (as previously described) and machine calibration was completed in erect standing, with standing resting lumbar lordosis angle recorded. Participants were instructed to complete a single movement into maximal lumbar flexion, lumbar extension, maximal anterior and posterior pelvic tilt, and into the simulated landing position.
Maximal Lumbar Flexion:
Participants sat on the floor with a foam roller placed under their knees, to reduce hamstring influence on the pelvis and sagittal spine orientation. In this position, the participant’s pelvis was placed into maximal posterior pelvic tilt, and instructions to maximally flex forward into a pike position in reaching for the toes, were then given to achieve end range (Figure 2a).

Maximal Lumbar Extension:
In the prone ‘cobra’ position, participants were instructed to maintain iliac spine position, horizontal with the floor and to maximally extend the lumbar spine. Maximal thoracic extension and cervical extension were required to ensure maximal lumbar range was achieved, secondary to regional interdependence and varied contribution of ROM from upper and lower lumbar segments (Figure 2b).

Simulated Landing Task (SLT):
Finally, subjects performed the SLT using the previously determined set up, making contact with the electronic scales, not exceeding the weight limit. (Figure 2c)

Data management and analysis:
Total lumbar spinal movements were calculated, by the determining the difference between the upper and lower sensor measurements in the sagittal plane. Lumbar flexion in the sagittal plane was indicated by a positive value and lumbar extension a negative value from the calibrated standing position. LLS movements, driven by anterior and posterior pelvic tilt ROM, were taken from the lower sensor measurements. All maximal lumbar spine movements, total lumbar and LLS angles during the SLT were collated and descriptively analyzed using means and standard deviation. Total and LLS posture during the SLT was then considered in relation to The CCLLDM.

RESULTS
Participants were aged 16-29 years with a mean (SD) of 19.73 years (3.51), height 162.1cm (8.4) and weight 60.72kg (8.86). Mean standing lumbar lordosis was -30.80˚ (9.99). Maximal lumbar flexion and extension movements are presented in Table 1.

Mean (SD) maximal spinal movements were 64.23˚ (6.34) for lumbar flexion and -25.89˚ (11.14) for extension. During the SLT all participants performed lumbar flexion relative to the calibration position [mean 15.96˚ (8.80)]; considering the lumbar spine as a single segment. In relation to the parameters of motion of the proposed CCLLDM, Figure 3 presents the maximal lumbar spine movements and lumbar movement during the SLT. When considering the lumbar spine as a two segment model the LLS...
Mean values for maximal posterior pelvic tilt were 11.05˚ (9.41) and for anterior pelvic tilt were 39.52˚ (6.52). Mean values for LLS movement (i.e. pelvic tilt relative to the standing calibration position) were 31.18˚ (6.85). Data were missing for participant 14 secondary to apparatus error however the total ROM is presented.

**DISCUSSION**

This study provides the first normative data set of maximal lumbar spine ROM for an elite gymnastics population. Standing lumbar lordosis and maximal total lumbar spine ROM normative data provide reference values for asymptomatic individuals in this physically active population. The data also provide insight into total lumbar and LLS movement during a 'high-load, low-dynamic' controlled SLT, evaluated in the context of the newly proposed CCLLDM.

Mean maximal lumbar flexion (64.23˚) and lumbar extension (-25.89˚) ROM values were consistent with previous literature as measured with the CA6000 Spine Motion Analyzer and Epionics SPINE system. Troke et al8 reported median maximal lumbar flexion ROM values of 73˚ and 68˚ in males

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<th>Table 1. Lumbar spine movements.</th>
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<td>Anterior Pelvic Tilt</td>
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<td>Posterior Pelvic Tilt</td>
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<td>Lumbar spine as a single segment – simulated landing task</td>
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<td>Low lumbar spine (pelvic tilt) – simulated landing task</td>
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<td>ROM (Range of Motion)</td>
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**Figure 3.** Maximal lumbar spine movement and lumbar spine position as a single segment during Simulated Landing Task (SLT), in relation to CCLLDM.
and females respectively (measured in a standing position), in a sample of 405 asymptomatic individuals aged 16-90 years. Dreischarf et al, completing maximal lumbar flexion and lumbar extension movements in standing with knees extended, also demonstrated similar results with a sample of 115 participants, aged 20-29 years achieving mean values of 53.7˚ for maximal lumbar flexion and -31.1˚ for lumbar extension. Performing maximal movement measurement protocols in standing versus sitting and the greater lumbar spine ROM requirements for an elite gymnastics subgroup, may explain the increased mean maximal lumbar flexion ROM in the current study. As lumbar spine mobility has shown to reduce with increasing age, the broad age range and limited elite gymnastics population size, may also reflect the variance in maximal total lumbar spine ROM. Standing lumbar lordosis angles presented in the current study (-30.80˚) are also consistent with previous literature with mean lumbar lordosis of 36.4˚ demonstrated by Dreischarf et al22 and 38.9˚ by Mitchell et al17 in a sample of 107 nursing students with a mean age of 21 years. The current findings demonstrate that participants performed the SLT with the pelvis close to maximal anterior pelvic tilt range, suggesting LLS extension. LLS extension during a ‘high-load, low-dynamic’ control task may result in increased posterior neural arch load,19 which may be associated with vertebral pathology, highly prevalent in the gymnastic population.3,6 This is further supported by Mitchell et al17 who demonstrated participants performing LLS extension relative to the calibrated standing position during a stand to squat task. Wade et al4 measured lumbar spine posture during a drop jump landing from one meter, in twenty one female gymnasts (mean age ±SD = 13 ± 3 years). The mean lower lumbar spine position is extension, with the upper lumbar spine in flexion 0.1 seconds before and after the landing tasks. LLS extension would not have been evident when considering the spine as a single segment, further supporting the suggestion from the current study that considering the lumbar spine as a single segment does not reflect variation between upper and lower lumbar spine kinematics during a low dynamic control SLT.15

The CCLLDM presents measures for the ‘envelope of motion’11 associated with proposed optimal lumbar spine posture and compressive axial load distribution, during ‘high-load, low-dynamic’ control tasks. Establishing measures for the ‘envelope of motion’ enables identification of high risk lumbar spine postures, associated with increased spinal tissue load. The CCLLDM provides a framework for clinicians to identify sporting tasks associated increased spinal tissue axial load, facilitating load management strategies, with the aim of reducing time loss injury.38 With improved awareness of higher risk ‘low-dynamic’ control tasks, clinicians may be able to provide coaches with information regarding the cumulative biomechanical consequences of performing high-repetition sporting skills associated with increased spinal loads.

Limitations
A potential limitation is that data collection took place following a morning training session. Although the impact from viscoelastic hysteresis on lumbar spine ROM has been well demonstrated,12,39 as participants were part of the British Gymnastics program building towards The Olympic Games, morning activities could not be controlled for each participant. Lumbar spine compressive load biomechanics is grounded in single segment, cadaveric literature.7,12,15 Caution must therefore be used when transferring the results of this research to young, asymptomatic subjects.12 LLS, pelvic driven movement, occurring during the SLT reflects current research regarding lumbar spine kinematics4 however, transferability of results is limited as the pelvic tilt data presented is in relation to the lower sensor calibration position and does not provide a true reflection of relative movement into lumbar flexion, extension and pelvic tilt. Standardized positioning, as per the methods achieved in the current study, is therefore vital to ensure comparable data of maximal range to LLS position during the SLT. Clinicians should therefore consider pelvic driven data in relation to maximal anterior and posterior pelvic driven ROM, when implementing the described methodology.

CONCLUSIONS
The results of the current study provide the first normative data set for lumbar spine ROM for an elite asymptomatic gymnastics population. These data will provide clinicians with reference values when
developing rehabilitation programs following lumbar spine pathology. Lumbar spine posture during the SLTs further supports the importance of considering the lumbar spine as a minimum of two segments and provides analysis of posture during a simulated sporting task which may be associated with increased spinal tissue load. The CCLLDM has been developed for clinicians, synthesizing biomechanical literature investigating the impact of compressive axial lumbar load distribution on spinal tissues. The CCLLDM provides a model for clinicians to consider when developing rehabilitation programs and establishes a framework for identifying sporting activities associated with higher risk lumbar spine postures. Future studies should aim to identify sport specific tasks associated with end of range spinal positions. The CCLLDM requires further implementation and targeted research in varying sports to assess transferability. These data may ultimately enhance the ability of clinicians to develop lumbar spine injury prevention, rehabilitation, and load management strategies in the elite sporting population.

REFERENCES


ABSTRACT

Background: The goal of therapeutic exercise is to facilitate a neuromuscular response by increasing or decreasing muscular activity in order to reduce pain and improve function. It is not clear what dosage of exercise will create a neuromuscular response.

Purpose: The purpose of this study was to assess the effects following a three-week home program of a daily single exercise, the prone horizontal abduction exercise (PHA), on neuromuscular impairments of motor control as measured by scapular muscle EMG amplitudes, strength, and secondarily outcomes of self-reported pain and function between individuals with and without subacromial pain syndrome.

Study Design: Prospective Case-Control, Pilot Study

Methods: Twenty-five individuals participated; eleven with shoulder pain during active and resistive motions (Penn Shoulder Score: 77 ± 11) and 14 matched healthy controls (Penn Shoulder Score: 99 ± 27) (p < 0.001). Participants underwent baseline and follow up testing at three weeks including surface electromyography (EMG) of the serratus anterior, upper, and lower trapezius of the involved (painful group) or matched shoulder (control group) during an elevation task and maximal isometric shoulder strength testing. All participants were instructed in a PHA exercise to be performed daily (3 sets; 10 reps). Subjects logged daily exercise adherence. Neuromuscular adaptations were defined by changes in EMG amplitudes (normalized to MVIC) of serratus anterior, upper trapezius, and lower trapezius and strength. Secondary outcomes of self-reported pain and function were also compared between groups following the three-week intervention.

Results: After three weeks of a daily PHA exercise, the painful group demonstrated a greater decrease in baseline-elevated EMG amplitudes in the lower trapezius by 7% (95%CI 2.6-11%) during the concentric phase of the overhead lifting task (p = 0.006). EMG amplitudes of the healthy control group did not change at three-week follow-up. Additionally, the change in serratus anterior mean EMG amplitude in the painful group -1.6% (IQR -22.9 to 0.8%) was significantly greater (p = 0.033) than the healthy group change score, 2.5% (IQR -2.3 to 5.7%) during the eccentric phase (p = 0.034). While the painful group was weaker in abduction and flexion at baseline and at follow up, both groups had a significant increase in all strength measures (p≤0.014). Concurrent with increased strength and normalizing EMG amplitudes, the painful group significantly improved on the Penn Shoulder Score with a mean change 9.8 points (95%CI=7.0, 12.6) (p<0.001).

Conclusion: In this pilot case-control study, a single home exercise performed daily for three weeks demonstrated neuromuscular adaptations with improvements in muscle activity and strength. These were concurrent with modest, yet significant improvements pain and function in individuals with mild rotator cuff related shoulder pain.

Level of Evidence: 3

Key words: Electromyography, impingement, muscle strength, rehabilitation, subacromial pain,

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Conflict of Interest: All authors have no conflict of interest related to this manuscript.
INTRODUCTION
Abnormal scapular kinematics and altered scapular muscle electromyographic activation levels during humeral elevation are associated with rotator cuff related shoulder pain. Decreased or excessive scapular upward rotation are commonly reported scapular motion alterations. However, there are challenges to clinicians’ ability to reliably identify specific alterations leading to refined scapular dyskinesis tests that indicate presence or absence of alterations in scapular motion. Corresponding to these altered scapular biomechanics during shoulder elevation are alterations in motor control, as evidenced by abnormal electromyographic (EMG) activity of scapular musculature in individuals with rotator cuff related shoulder pain relative to normal controls. Motor control impairments likely contribute to abnormal scapular motion and rotator cuff related shoulder pain. These motor control impairments appear to include the relative balance of scapular muscles, such as increased activation of the upper trapezius and altered activation and onset timing in the lower trapezius and serratus anterior muscles.

Exercise programs that not only focus on scapular muscle strengthening, but emphasize motor control, including quality of movement and timing, have been advocated for the treatment of individuals with subacromial pain syndrome and included in shoulder sports injury prevention programs. Prior work from De May, et al. found that an intervention consisting of four scapular focused exercises over a six-week period in overhead athletes with subacromial pain resulted in a clinically and statistically significant improvement in self-reported pain and function measured by the shoulder pain and disability index. Furthermore, changes in motor control were also found with reduced EMG amplitudes in the upper trapezius during elevation and onset timing of lower trapezius and serratus compared to upper trapezius. Thus, improvements in pain and function appear to be related to changes in scapular muscle motor control following a six-week exercise program. However, it is not known if strength improvements occurred simultaneously as this was not a variable reported in the DeMay et al. study. The prone humeral horizontal abduction (PHA) exercise was one of the four exercises included in their study.

The PHA exercise has been consistently included in many shoulder rehabilitation and shoulder sports injury prevention programs. The PHA has demonstrated greater scapular kinematic changes in upward rotation, posterior tilt, and external rotation compared to the resting position and high activation levels of both posterior scapular and rotator cuff musculature. While DeMay et al. showed changes following six weeks of training, neuromuscular adaptations can occur in as few as two to three weeks prior to physiological muscle change including hypertrophy.

Ultimately, common goals of rehabilitation for patients including athletes with shoulder pain are to improve function and reduce pain. Exercise has been proposed as an effective intervention to achieve these goals. However, patients often struggle with adhering to home exercise regimens due to multiple barriers such as low physical activity, time, lack of understanding, or poor self-efficacy. Clinicians are frequently faced with the dilemma of which exercises to prescribe to achieve the rehabilitation goals without over-burdening the patient. Perhaps only one exercise targeting scapular and rotator cuff strength may be effective as a home program to improve impairments in neuromuscular control, pain, and function in individuals with subacromial pain. Early perceived positive changes in pain, function and/or impairments have been shown to facilitate better outcomes over the course of physical therapy treatment. Furthermore, if a simple intervention results in perceivable improvements in just a few weeks, then patients may be willing to accept a more comprehensive intervention. Therefore, the purpose of this study was to conduct a pilot study to assess the effects following a three-week home program of a daily single exercise, the PHA, on neuromuscular impairments of motor control as measured by scapular muscle EMG amplitudes, strength, and secondarily outcomes of self-reported pain and function between individuals with and without subacromial pain syndrome. The authors hypothesize that greater changes in neuromuscular impairments as measured by scapular muscle EMG amplitudes and force generated with strength tests, as well as a improvement in secondary measures of pain and function, will be greater in the painful
shoulder group following a three-week program of a daily bout of a single exercise, the PHA.

METHODS

Participants
Twenty-five adults volunteered to participate in this prospective case-control study. Participants were recruited as a sample of convenience from the university community. Eleven individuals with rotator cuff related shoulder pain (painful group) and 14 healthy participant case-controls (healthy group) were recruited (Table 1). All participants signed a University Institutional Review Board approved written informed consent prior to initiating test procedures.

Participants from either group were excluded if they were for any reason unable to perform the PHA shoulder exercise, had allergies to adhesive, neurological disorders or positive findings on an upper quarter myotomal or dermatomal screen other than reduced shoulder strength, limitations in shoulder passive range of motion (other than limitations in internal rotation or horizontal adduction characteristic of posterior shoulder tightness), or a history of neck or shoulder fracture or surgery. Participants in the painful group were included if shoulder pain was reproduced during active, passive or resistive shoulder motion with a clinical exam. Specifically participants were included if one of passive tests, the Hawkins and/or Neer impingement signs, were positive and pain was reproduced with resisted abduction or external rotation or a painful arc was present during active abduction. Painful participants were excluded if the shoulder pain was greater than a 7/10 on the numeric pain rating scale so that strengthening would be tolerated\textsuperscript{30} or passive range of motion was limited. Healthy participants were recruited if they had no complaints of shoulder or neck pain within the last six months and included if they had no reproduction of pain during active, passive shoulder range of motion in all planes (sagittal, coronal, transverse) or resisted shoulder motion in abduction, flexion or internal/external rotation at 90 degrees of abduction. Also participants had to demonstrate normal cervical spine range of active motion in all planes without pain. Participants in the painful group were not currently seeking treatment. Healthy participants were matched by sex and hand dominance of the shoulder tested to those in the painful group.

As part of the inclusion/exclusion process, all patients' cervical and shoulder mobility were evaluated using standard clinical measures of active, passive, and resistive range of motion. Scapular dyskinesis testing was performed as described previously, with five repetitions of abduction and flexion while holding a three- or five-pound weight.\textsuperscript{7} The test was considered positive if obvious dyskinesis, noted by winging, excessive elevation or protrusion, or dysrhythmia during arm elevation or lowering.\textsuperscript{7} The clinical screening examination included a neurological upper quarter myotomal and dermatomal screen, rotator cuff testing to rule out large/massive rotator cuff tears with drop arm, external rotation lag and horn blowers signs,\textsuperscript{31} Neer and Hawkins impingement tests, presence or absence of the sulcus sign, anterior-posterior drawer, and apprehension testing.\textsuperscript{32-34} All testing was completed by a licensed physical therapist.

<table>
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<tr>
<th>Table 1. Mean (± standard deviation) participant demographics and PENN Shoulder Score.</th>
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<td>All Participants</td>
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<td>Gender</td>
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<td>PENN Shoulder Score</td>
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* Statistically significant difference between groups
All participants completed a physical activity readiness questionnaire, a medical history questionnaire, and the Penn Shoulder Score during baseline evaluation. The Penn Shoulder Score is a validated, self-reported, regional disability scale from zero to 100 points. One hundred points is a perfect score indicating no pain, high satisfaction, and normal function. The Penn Shoulder Score has strong reliability and a minimal detectable change score of 12 points.\textsuperscript{35} The Penn Shoulder Score was administered at baseline testing and after the three-week intervention.

Procedures
Participants attended two sessions three weeks apart and underwent the same procedures on both sessions. Scapular neuromuscular activity of the upper trapezius, lower trapezius, and serratus anterior was measured via surface EMG during the arm elevation task. The participants’ skin was prepared for surface electrode placement, shaved if needed, lightly debrided with fine sandpaper, and cleaned with alcohol. Bipolar surface electrodes (Blue Sensor; Glen Burnie, MD) were placed parallel to the muscle fibers with a two-centimeter inter-electrode distance on the serratus anterior,\textsuperscript{36} upper portion of the trapezius\textsuperscript{37} and lower portion of the trapezius\textsuperscript{38} (Table 2). A surface ground electrode was placed on the contralateral acromion process. An electrogoniometer (SG110, Biometrics, Ladysmith, VA, USA) was placed on the shoulder, across the scapular spine and distal to the deltoid, to capture arm elevation motions. The EMG channel and electrogoniometer leads were connected to a portable amplifier (Run Technologies, Mission Viejo, CA). Electrode placement was visually confirmed with resisted contractions of the instrumented muscles while verifying the EMG activity with an oscilloscope. The EMG amplitudes of each muscle were recorded while standing with the arms at the side.

The EMG amplitude data were collected during maximum voluntary isometric contractions (MVIC) in order to compare amplitude data for the task of interest between participants. In order to obtain strength measures, a hand-held dynamometer (JTech Commander, Midvale UT) was used during all MVIC testing. Participants performed two five-second MVICs for each scapular muscle, using standardized test positions in randomized order (Table 2).\textsuperscript{21,39-41} Participants were familiarized with the MVIC procedure by

<table>
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<th>EMG collected</th>
<th>Electrode Location</th>
<th>MVIC/Strength test position</th>
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<tr>
<td>Upper Trapezius</td>
<td>A mark was made on the skin at the midpoint on a line joining the C7 spinous process and tip of the posterior lateral angle of the acromion. The electrodes were placed over a point 1/2 distance between this point and the posterior lateral angle of the acromion\textsuperscript{37}</td>
<td>Abduction: The participant abducted his/her arm to 90\textdegree{} with thumb pointing up. The hand held dynamometer was applied just proximal to the elbow with the participant sitting upright. The participant abducted his/her arm up against resistance applied through the humerus</td>
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<td>Lower Trapezius</td>
<td>The arm was elevated in abduction to 125\textdegree{} and the electrodes were placed at the midpoint from the T7 spinous process to the inferior angle of the scapula in line with muscle fibers obliquely superior and laterally\textsuperscript{38}</td>
<td>Prone Elevation: In a prone position, the participant abducted his/her arm to 125\textdegree{} with thumb up. Subject was asked to push up against the hand held dynamometer that was placed on distal arm just proximal to the radial styloid.</td>
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<td>Serratus Anterior</td>
<td>With the arm elevated to 125\textdegree{} the electrodes were places over the 7th intercostal space, just anterior to the fibers of the latissimus dorsi in line with the serratus anterior muscle fibers\textsuperscript{36}</td>
<td>Flexion: With subject seated, resistance was applied with the hand held dynamometer to distal arm proximal to the wrist in a perpendicular direction with the humerus elevated to 125\textdegree{} in the sagittal plane</td>
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first performing a submaximal practice trial for each isometric make test performed. Strength, defined as peak force generated, was simultaneously recorded with hand held dynamometer during the MVICs. Participants were given one-minute of rest between trials. To assist with determining maximal effort, the output of the two maximal effort trials had to be within 10% of each other. Additional trials were captured until two highest values were within 10%. The average maximal force (kg) produced during the two maximal trials (MVIC) was calculated and then normalized to each subject’s body weight (kg) to yield strength as a % body weight. Three strength tests/MVIC positions were performed: shoulder abduction with the arm at 90°, prone elevation with the arm at 125° of abduction, and seated shoulder flexion at 125° (Table 2). MVIC EMG value used for normalization was determined based on highest recorded EMG amplitude regardless of test position, due to the synergy between these muscles.42

Arm elevation task
Each participant was asked to perform ten repetitions of weighted bilateral elevation in the scapular plane as previously described.7,16 The amount of weight used was based on the participant’s body weight. Participants with a body weight less than 150 pounds (68 kg) used three-pound weights, (1.4kg) and those with a body weight equal or greater than 150 pounds (68kg) used five-pound (2.3kg) weights. The weights were held in each hand, and EMG data was collected during arm elevation. A metronome was used to control the rate of elevation; a full elevation cycle was achieved in a four second count with two second count for maximal concentric elevation and two second count for eccentric lowering. Practice trials were provided to achieve the desired rate and range of motion of arm elevation.7 EMG activity was recorded during the entire duration of the elevation trials.

Prone Horizontal Abduction Exercise Intervention
The PHA is a commonly used exercise in both preventive and rehabilitation interventions.19,29,43 Participants were instructed to perform a prone horizontal abduction (PHA) exercise with verbal and tactile feedback to ensure correct performance. The therapist positioned and supported the participant’s arm in the PHA position (abduction to 100° with external rotation) while manually guiding the scapula into depression and retraction as a cue for the desired scapular movement with the exercise. Verbal cues to fully externally rotate the humerus, to tip scapula back and downards, and to avoid a shrugging motion were also provided. Tactile feedback with tapping was provided to the lower trapezius to facilitate activation.44 The participant was then asked to demonstrate the full exercise while additional verbal and tactile feedback was provided. The efficacy of this exercise instruction on scapular muscle activity has been previously demonstrated.44 Once proper technique was achieved, the participant was asked to perform three sets of ten repetitions daily at home. Participants were provided with a weight to use at home that was equal to two percent of his or her bodyweight, as adapted from De Mey, et al.16 Additionally, participants were given written instructions that described how to perform the PHA exercise and an exercise log to record daily exercise adherence.41

EMG Data Processing
A 16-channel EMG system (Run Technologies, Mission Viejo, CA) was used to record muscle activity. All raw EMG data were transmitted at 2000 Hz via a fiber optic cable through a Myopac transmitter unit (Run Technologies, Mission Viejo, CA) to the receiver unit. Unit specifications for the Myopac included a common mode rejection ratio (CMRR) of 90 dB, an amplifier gain of 2000 for the surface EMG electrode, and an amplifier gain of 1000 for the electrogoniometer. Using Datapac 5 software (Run Technologies, Mission Viejo, CA), all raw EMG data were processed digitally with a passive demeaning filter to correct for a DC offset. All raw EMG data had a high pass fourth order finite impulse response filter set at 10.0 Hz, then were full-wave rectified. Finally, a low pass cut-off of 6.0 Hz with a fourth order Butterworth filter was used to smooth the data.41

The MVIC was determined by identifying the highest 500ms window of EMG activity during the two five-second maximal isometric trial for each muscle tested. The highest 500ms of EMG activity recorded during resting was subtracted out of all MVIC and
exercise recorded EMG activity as background noise. The mean EMG amplitudes were normalized to the MVIC EMG amplitudes to represent mean muscle activity. The electrogoniometer was used to identify two, concentric and eccentric, phases of the elevation task. The reproducibility of the experimental procedure and EMG data processing was good to excellent as previously established. Trials four through eight were averaged for each phase separately to represent each participant's mean EMG amplitude during the elevation task. This processing was performed to derive mean EMG concentric and eccentric EMG amplitudes for each muscle at baseline and discharge to be used for statistical analyses.

**Statistical Analysis**

As data were obtained to generate preliminary estimates of changes in neuromuscular adaptations in this pilot case-control study, no a priori sample size analysis was performed to determine statistical power to detect between group differences in treatment effects. All data were evaluated for normality using the Shapiro-Wilk test of normality and Q-Q plot. Chi-square and independent t-tests were used to compare baseline group participant demographics and three-week follow up self-reported adherence to the daily PHA exercise as a proportion of days completed. To determine the effects of a three-week single PHA exercise home program on changes in neuromuscular adaptations during the active elevation task and shoulder strength between groups, separate 2x2 repeated-measures ANOVAs were used to evaluate change between groups over time in mean EMG amplitudes (concentric; eccentric phases of elevation task) in the lower trapezius, upper trapezius and normalized maximal strength (% body weight) in abduction, flexion, and prone elevation. The within participant factor was time (baseline, three-week follow up) and the between-participants factor was group (painful, healthy). In the event of statistical significance, post-hoc testing was performed using pairwise comparisons and a Bonferroni corrected alpha. To evaluate differences over time between groups in the Penn Shoulder Score and serratus anterior mean concentric and eccentric EMG amplitudes during the elevation task, separate non-parametric Mann-Whitney U tests were performed to compare change scores from baseline to discharge between the two groups (healthy and painful) due to the non-normal distribution of these data. Alpha was set at 0.05 for all analyses.

**RESULTS**

Eleven individuals with shoulder pain (painful group) and 14 healthy participant case-controls (healthy group) completed the study. Baseline characteristics of the two groups were not significantly different for age, height or weight (Table 1). However, as expected the painful group had lower Penn Shoulder Scores than the healthy group at baseline (p<0.001). There were no significant differences (p=0.581) in the proportion of self-reported adherence to the daily PHA exercise between the painful group (83.1%) and the healthy group (79.1%). However, only 8/11 (72%) subjects in the painful group and 9/14 (64%) subjects the healthy control group returned the compliance log.

There was a significant group by time interaction (p =0.045) with the lower trapezius muscle during the concentric phase of arm elevation. The painful group demonstrated greater lower trapezius EMG amplitudes at baseline, and a significant (p=0.006) 7% (95%CI 2.6-11%) mean reduction in EMG amplitudes at three-week follow-up compared to no change (p>0.05) in the healthy group. Similar results were found in lower trapezius EMG amplitudes during the eccentric phase. During eccentric phase arm elevation task, the painful group had greater EMG amplitude in the lower trapezius muscle at baseline. The reduction in EMG amplitude at follow up did not reach statistical significance for the time x group interaction (p=0.081). However, there was a statistically significant main effect of group given the higher baseline and follow up eccentric lower trapezius EMG amplitudes in the painful group (5.8%; 95%CI 2.1-9.5%) across both time points (p=0.004) (Table 3).

The upper trapezius EMG amplitudes did not demonstrate a group by time interaction in either the concentric or eccentric phases of arm elevation (p=0.33, p=0.086), respectively (Table 3). While there were trends of main effect of group (p=0.09) with the painful group demonstrating greater upper trapezius mean EMG amplitudes in both phases of elevation at baseline and follow up, this did not quite reach statistical significance in either phase.
Additionally there were trends towards a main effect of time with both groups showing a mean of 3-4% decrease in upper trapezius EMG amplitudes from baseline to three-week follow up, yet this did not reach significance during the concentric (p=0.067) or eccentric (p=0.092) phases, respectively.

The serratus anterior EMG amplitude change scores were calculated with a negative number indicating a reduction in EMG amplitude from baseline to three-week follow up, yet this did not reach significance during the concentric (p=0.067) or eccentric (p=0.092) phases, respectively.

The serratus anterior EMG amplitude change scores were calculated with a negative number indicating a reduction in EMG amplitude from baseline to three-week follow up. Results of non-parametric Mann-Whitney U tests analyses show that during the concentric phase of arm elevation, there were similar changes in the painful group -9.4% (IQR -36.5 to 9.7%) compared to the healthy group change 3.2% (IQR -8.2 to 19.8%) which were not statistically significant (p =0.075). However, during arm lowering (the eccentric phase of the task), the change in serratus anterior mean EMG amplitude in the painful group -1.6% (IQR -22.9 to 0.8%) was significantly greater (p=0.033) than the healthy group change score, 2.5% (IQR -2.3 to 5.7%).

Results of individual 2-way repeated-measures ANOVA used to evaluate change in strength, revealed no difference in the change in maximal normalized force generated between the groups over time with a group by time interaction of p >0.59 (Table 4). However, there was a significant increase in all three strength measures in both groups demonstrating a main effect of time (p≤0.014). (Table 4) Additionally, the healthy group generated more force with strength tests in abduction (p=0.02, 3.4%; 95%CI = 0.6, 6.2) and flexion (p=0.03, mean = 2.6%; 95%CI = 0.3, 4.9) than the painful group, across both time points. While this was true for abduction and flexion, there were no significant differences (p=0.08); between the groups in force generated with the prone elevation at either time point (mean difference 1.8%, 95%CI = -0.2, 3.7). (Table 4) Lastly, there was a significant difference in the change in the Penn Shoulder Score between groups (p <0.001) with an improvement in the Penn Shoulder Score in the painful group by a mean of 9.8 points (95%CI = 7.0, 12.6) compared to no change in the healthy group (mean change = -0.43 points; 95%CI = -2.9, 2.1).

DISCUSSION

The results of the current study suggest neuromuscular adaptations occur following a three-week program of a single exercise, PHA, performed daily in individuals with and without rotator cuff related shoulder pain. Interestingly, there appeared to be carry-over effects with changes in muscle activity (EMG amplitudes) during a functional elevation task that occurred following a daily three-week PHA exercise program, but primarily in the painful group. In the painful group, baseline mean EMG amplitudes of the lower trapezius and serratus anterior were elevated and significantly reduced following the three-week PHA exercise program in both the concentric and eccentric phases of the elevation task, respectively. Greater EMG activity in the lower trapezius and serratus at baseline in the painful group suggests greater muscle activity is required to perform the submaximal arm elevation task at baseline compared to three-week follow up testing. This decrease in muscle activity needed to perform the elevation task occurred concurrent with a modest but significant increase in shoulder strength increase following a three-week daily single exercise that targeted the posterior shoulder musculature. This supports the hypothesis that neuromuscular adaptations occurred following a three-week PHA. Furthermore, the mean lower trapezius and serratus anterior EMG amplitudes were lower at baseline.

<table>
<thead>
<tr>
<th>Table 3. Results of change in EMG amplitudes as percentage of MVIC.</th>
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<tr>
<td>Healthy Group</td>
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<tr>
<td>(n=14); Painful Group (n=11)</td>
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<td>Eccentric LT†</td>
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* = Indicates a significant group by time interaction
† = Indicates a significant change between baseline and 3-week follow up
‡ = Indicates a significant main effect of group (p=0.004). The painful group had significantly greater EMG amplitude at both time points compared to the healthy group.

UT = Upper Trapezius
LT = Lower Trapezius
and did not significantly change in the healthy control group following the three-week intervention. Concurrent with neuromuscular changes, the painful group also had a significant improvement in the Penn Shoulder Score from baseline to three-week follow up, although not beyond the minimal detectable change. Results of this pilot study are encouraging, since recent research has shown that early changes to physical therapy interventions can occur and are predictive of future results. The current study results indicate that individuals with rotator cuff related shoulder pain demonstrate neuromuscular adaptions following a three-week single PHA exercise program approximating mean muscle activity and strength found in healthy individuals as self-reported pain and function improves.

**Neuromuscular Adaptations: EMG amplitudes**

In the current study, the painful group had a significant decrease in lower trapezius and serratus anterior EMG amplitude during the arm elevation task from baseline to three-week follow up compared to the healthy control group. These changes are consistent with prior research showing neuromuscular change occurs with exercise in short-term follow up. The significant change found in the lower trapezius is likely due to the specificity of the exercise prescribed. Prior work has shown that the PHA exercise elicits high levels of lower trapezius activity, 59% of MVIC during the concentric phase of the exercise, compared to the serratus anterior and upper trapezius with 12.5% and 24% MVIC, respectively. Furthermore, the verbal and tactile exercise instruction provided at baseline was intended to facilitate greater lower trapezius muscle activity and reduce excessive upper trapezius activity during the PHA exercise. The effects of the specific verbal and tactile instruction to facilitate targeted lower trapezius muscle performance with the PHA have been previously demonstrated. Interestingly, there do appear to be carry-over of the effects of a PHA exercise to the elevation task, specifically with reduced lower trapezius EMG amplitudes by 7% (p=0.006) in the concentric phase at three-week follow up (Table 3). This is consistent with findings of prior research by DeMay, et al. who found a 15% reduction in lower trapezius muscle activity following a six-week scapular

| Table 4. The normalized strength, force generated as percent of bodyweight, at baseline and discharge. |
|-------------------------------------------------|-------------------------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Healthy group (n=14)                            | Baseline | 3-week Follow up | Interaction group x time (p-value) | Main effect of Time (mean difference; 95%CI; p-value) | Main effect of group (mean difference; 95%CI; p-value) |
| Painful group (n=11)                            |         |                 |                                  |                                                 |                                                |
| **Abduction**                                   |         |                 |                                  |                                                 |                                                |
| Healthy                                         | 13.2±3.6 | 14.5±3.8        | 0.59                             | 3.4% (0.6-6.2%)                              | p=0.02†                                         |
| Painful                                         | 9.6±2.8  | 11.2±3.1        |                                  |                                                 |                                                |
| Total (n=25)                                     | 11.6±3.6 | 13.1±3.8        | 1.5% (0.9-2.0%)                  | p<0.001*                                       |                                                |
| **Prone Elevation**                             |         |                 |                                  |                                                 |                                                |
| Healthy                                         | 7.7±2.7  | 9.8±3.1         | 0.85                             | 1.8% (-0.2 – 3.7%)                           | p=0.08                                          |
| Painful                                         | 6±2.2    | 8±1.3           |                                  |                                                 |                                                |
| Total (n=25)                                     | 6.9±2.5  | 8.9±2.6         | 2.0% (1.3-2.6%)                  | p<0.001*                                       |                                                |
| **Flexion**                                     |         |                 |                                  |                                                 |                                                |
| Healthy                                         | 11.5±3.2 | 12.5±3.3        | 0.97                             | 2.6% (0.3-4.9%)                              | p=0.03†                                         |
| Painful                                         | 8.9±2.5  | 9.8±2.3         |                                  |                                                 |                                                |
| Total (n=25)                                     | 10.3±3.2 | 11.3±3.2        | 1.0% (0.2-1.7%)                  | p=0.014*                                       |                                                |

* indicates significant main effect of time. Results represent change regardless of group
† indicates significant main effect of group. Results represent group differences regardless of timepoint
muscle strengthening program in individuals with subacromial pain syndrome. The current results are consistent with these prior study results with approximately half the reduction in excessive mean lower trapezius EMG activity, in only three weeks of a single PHA exercise. Furthermore, only the current pilot study included a healthy control group that had lower mean EMG activity during the elevation task at baseline that did not significantly change at follow up. Inclusion of the healthy control group also allowed the authors to evaluate change scores in the non-normally distributed serratus anterior EMG amplitudes between groups from baseline to follow up in the current study. There was a statistically significant change from baseline to discharge (p=0.033) in mean serratus anterior amplitudes during the eccentric phase of the elevation task in the painful group -1.6% (IQR -22.9 to 0.8%), compared to the healthy group. In previous research by DeMey et al., similar mean changes (2%) were not significant following a six-week exercise program in individuals with subacromial pain syndrome.

The relative decreases in EMG amplitudes found in the lower trapezius and serratus anterior during a functional task following a three-week strengthening program are expected can be an indication that muscular demands are diminished. Repeating the same arm elevation task prior to and following a training intervention, one would expect that the task would be less demanding after the intervention. Data supports this observation in the current case-control pilot study, even though statistical significant differences were not always achieved. Patients with shoulder pain were prescribed exercises that are intended to strengthen and improve motor control of the target muscles to reduce the heightened EMG activity during a submaximal functional task. In this study, the authors' observed that a single PHA exercise altered neuromuscular activity used to perform a common task with activities of daily living that is often painful in the population with rotator cuff related pain.

While neural adaptations may be one rationale for the reduced EMG amplitude results in the painful group, consideration must also be given to methodology used in this study that required both the painful and healthy groups to perform a maximal voluntary isometric contraction. The maximal EMG amplitude during the MVIC was used to normalize the EMG data during the functional task in both painful and healthy groups. This introduces a concern that neuromuscular changes found in the current study may not be attributed to neuromuscular adaptations in the painful group, but may be simply due to a reduction in pain with the MVIC with the follow up testing. In the current study the authors did not capture pain ratings during the MVIC in the painful group. However, to address this potential confounder, the raw EMG microvolts recorded during the MVIC that were used to normalize the EMG amplitudes for both groups at both time points were analyzed using a non-parametric Wilcoxon Signed Rank test to determine if meaningful changes occurred between testing days. As shown in Figures 1 and Figure 2, there were no significant differences between EMG amplitudes used to normalize the task EMG mean amplitude data for either group between baseline and three-week follow up (p >0.11). Given little to no change in the MVIC EMG amplitude data between baseline and follow up in the painful group, authors suggest that changes found in the mean MVIC normalized EMG amplitudes with the elevation task can be attributed to true neuromuscular adaptations.

### Neuromuscular Adaptations: Strength

Over the three weeks of the current study revealed small but consistent and statistically significant strength gains of one to two percent bodyweight in both groups. It is known that progressive resistance exercise increases strength, but few studies

![Figure 1. Box plot of healthy subjects' microvolts during maximal voluntary isometric contraction testing for elevation, abduction, and prone elevation.](image)
relate these gains specifically to shoulder rehabilitation. In the current study, both healthy and painful groups demonstrated and increase in isometric maximal force production measured by a handheld dynamometer in abduction, flexion and prone elevation by 1-2% body weight. Given the mean body weight of participants in the current study (72kg; 158lbs), maximal isometric force generated in shoulder flexion gains would equate to an increase from 7.4kg to 8.1kg (16.3 to 17.8 lbs) in both groups. These results are comparable to the previously reported mean strength in shoulder flexion values in healthy adults and those with rotator cuff related shoulder pain 6.8kg to 7.7kg (15.0 to 16.9lbs). With shoulder abduction strength testing, current study results equate to an increase in maximal force generated from 8.4kg to 9.4kg (18.5 to 20.7lbs) following a three-week PHA daily exercise in both groups. The current study results provide evidence that over a short period of training, neuromuscular adaptations with both changes in muscle EMG activity and strength occur from a single shoulder exercise over a three-week period of daily training in individuals with rotator cuff related shoulder pain. This is an important finding with value-based healthcare, as clinicians search for ways to overcome the poor adherence to rehabilitation exercise.

Rehabilitation faces the constant challenge of ensuring patient exercise adherence. Perceived simplicity and short duration of treatment, immediacy of benefit, and absence of side effects are known factors that increase patient adherence. Performing only one effective exercise confronts these perceived obstacles to adherence and would benefit those patients with limited motivation and time. During the course of the current study, 17/25 participants returned their exercise logs. From the 17 logs received, it was determined that the adherence rate to the daily exercise was 68%. This is certainly on the higher end of reported compliance with home exercise programs as previous studies have found compliance to any or all of the HEP to be 60-75%. This assumes that individuals who did not return the exercise logs had a similar adherence rate, which is not likely. However, there were no differences between groups in the proportion who did not return logs in our study. Daily PHA exercise offers clinicians the statistically significant improvement in the Penn Shoulder Score by a mean of 9.8 points over a three-week period. A minimal detectable change of 10.7 points in patients who start with a Penn Shoulder Score above 76, has been reported to be clinically meaningful which is less than one point short of change in the current cohort. Similarly, with a different metric measuring shoulder function, De Mey et al demonstrated an 18-point improvement on the SPADI which resulted from four exercises over a six-week period. In three weeks of a single exercise, an approximate ten percent improvement in self-reported pain and function was observed. The De Mey et al study examined the effects of four exercises over six weeks, which showed almost 20% improvement in self-reported function. The results of this current study demonstrate similar trends of improvement as the previous study and strengthen the value of the neuromuscular changes found in the painful group with a three-week PHA exercise. It appears that neuromuscular changes are also associated with early patient-centered changes in pain and function obtained with a streamlined home exercise program consisting of one exercise. This is important, because early improvement is a positive predictor of final outcomes in patients with shoulder pain.

Self-reported Pain and Function

Pain and function were measured using the Penn Shoulder Score. The painful group showed statistically significant improvement in the Penn Shoulder Score by a mean of 9.8 points over a three-week period. A minimal detectable change of 10.7 points in patients who start with a Penn Shoulder Score above 76, has been reported to be clinically meaningful which is less than one point short of change in the current cohort. Similarly, with a different metric measuring shoulder function, De Mey et al demonstrated an 18-point improvement on the SPADI which resulted from four exercises over a six-week period. In three weeks of a single exercise, an approximate ten percent improvement in self-reported pain and function was observed. The De Mey et al study examined the effects of four exercises over six weeks, which showed almost 20% improvement in self-reported function. The results of this current study demonstrate similar trends of improvement as the previous study and strengthen the value of the neuromuscular changes found in the painful group with a three-week PHA exercise. It appears that neuromuscular changes are also associated with early patient-centered changes in pain and function obtained with a streamlined home exercise program consisting of one exercise. This is important, because early improvement is a positive predictor of final outcomes in patients with shoulder pain.
opportunity to prescribe an intervention that may
be performed without specialized equipment while
also promoting functional and strength gains that
match patient concerns.

A statistically significant difference was not obtained
for the painful group in all outcomes measured
in this study. Strong trends of improvement were
observed in those that were not statistically signifi-
cant in the painful cohort. This provides further evi-
dence that a streamlined, efficient, home exercise
program may improve neuromuscular impairments,
self-reported function and reduce pain in individu-
als with mild rotator cuff related shoulder pain that
were not actively seeking treatment. Prior studies
have demonstrated higher adherence with a home
exercise program when the program consists of
fewer exercises in a military population53 (three ver-
sus six exercises) and with an elderly population54
(two compared to eight exercises). Currently, there
is no evidence on the dosing necessary to achieve
patient outcomes in patients with rotator cuff related
shoulder pain. While the current pilot study results
suggest a single exercise may result in neuromuscu-
lar changes with a home program in patients with
mild pain and functional loss in three weeks, an
adequately powered larger study of patients seeking
rehabilitation is warranted.

There are limitations due to the nature of this pilot
study case-control design. The study had a small
sample of convenience, limiting the generalizability
of the conclusions. The small sample also limited
the authors’ ability to perform any planned sub-
group analysis of adherent versus non-adherent par-
ticipants. With a small sample size, the study results
may also be influenced by a type II error. While sta-
tistically significant changes were not demonstrated
in all of the outcome measures, trends were found in
most of the other non-significant outcomes. Results
certainly provide evidence of feasibility that neuro-
muscular adaptations may occur with a single exer-
cise in three weeks in individuals with rotator cuff
related shoulder pain and justification for future
study with larger sample size. The authors did not
assess whether participants were participating in a
strengthening program prior to enrollment; how-
ever, individuals were asked to refrain from other
upper body strength training during the three-week

period. Participants in the current study with pain-
ful shoulders were mildly impaired as determined
with the Penn Shoulder Score (77/100) and were not
actually seeking treatment. Thus this daily three-

week single exercise intervention was not tested on
patients with painful shoulders seeking care. Result
of the current study are however, generalizable to a
younger, physically active population that are expe-
riencing mild symptoms, which further supports
the use of the PHA exercise in both rehabilitation
and injury prevention programs for young adult
athletes.43

CONCLUSIONS
To the authors’ knowledge, there is no evidence dem-

onstrating the short-term effects of a single shoulder
exercise on neuromuscular adaptations, specifically
muscle activity and strength, as these may relate
to changes in pain and function in individuals with
rotator cuff related shoulder pain. Pilot studies are
necessary to justify larger more costly and poten-
tially burdensome studies in patients, particularly
when feasibility, or concern for equipoise due to
treatments prescribed by the clinicians may be a
challenge. The modest improvements in strength
and associated decreases in baseline elevated EMG
amplitudes in individuals with rotator cuff related
pain in this pilot study substantiates the notion that
early neural adaptations can occur during the early
phases (three weeks) of a rehabilitation program
with a single strengthening exercise performed at
home.25 Furthermore, these neuromuscular adapta-
tions are associated with significant improvements
in patient-rated outcomes measured by the Penn
Shoulder Score. In the time of emerging value-based
healthcare, clinicians may want consider the poten-
tial for improvements gained by one effective exer-
cise that the patient is likely to perform, rather than
many exercises that may overwhelm the patient and
lead to diminished self-efficacy, adherence, and out-
comes. This study provides evidence that a single
exercise of PHA may be a viable treatment option
in the short-term in individuals with mild pain and
functional loss due to rotator cuff related shoulder
pain, precipitating neuromuscular adaptations that
carry over into a functional overhead lifting task.
Future trials should consider comparison of neuro-
muscular control and patient related outcomes as
it relates to exercise dosage at several time points during a course of rehabilitation to identify a typical recovery trajectory. Additionally, other factors including genetic or psychosocial phenotypes that may or may not respond to a streamlined home program may impact study results warranting further study.

REFERENCES


ABSTRACT

Background: Overuse injuries are common in volleyball; however, few studies exist that quantify the workload of a volleyball athlete in a season. The relationship between workload and shoulder injury has not been extensively studied in women’s collegiate volleyball athletes.

Hypothesis/Purpose: This study aims to quantify shoulder workloads by counting overhead swings during practice and matches. The purpose of the current study is to provide a complete depiction of typical overhead swings, serves, and hits, which occur in both practices and matches. The primary hypothesis was that significantly more swings will occur in practices compared to matches. The secondary hypothesis was that greater swing volume and greater musculoskeletal injury frequency will occur in the pre-season than during the season.

Study Design: Prospective cohort

Methods: Researchers observed practice and match videos and counted overhead serves and attacks of 19 women’s collegiate volleyball players for two seasons. Serves, overhead hits, and total swings (serves + hits) were the dependent variables; event (matches and practice) along with position (defensive specialists, setter, outside hitter, and middle blocker) were the independent variables. Musculoskeletal injury frequency and swing volume workload were compared across pre-season and competitive season time periods.

Results: Across all positions except outside hitters twice as many total swings occurred in practices compared to matches (p = .002) resulting in an average of 19 (CI95 16.5, 21.5) more swings in practice than in matches. The average number of total swings during the pre-season 47.1 (CI95 44.1, 50.1) was significantly greater than average swings per session during the competitive season 37.7 (CI95 36.4, 38.9) (p < 0.001) resulting in a mean difference of 9.4 (CI95 6.1, 12.7) swings. The number of athletes limited in participation or out due to a musculoskeletal injury during the pre-season (2.9%) was greater than during the season (1.1%) (p = 0.042).

Conclusion: These findings support the primary hypothesis that women’s collegiate volleyball athletes swing more during practices than in matches. The higher average number of serves in the pre-season and the greater frequency of musculoskeletal injuries requiring participation restriction or removal from participation suggest that a concordant relationship may exist between workload and injury variables.

Level of Evidence: 2

Keywords: Attack, overuse, shoulder, volume, volleyball serve

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INTRODUCTION

It is estimated that over thirteen thousand female athletes participate in volleyball at the collegiate level.1 Musculoskeletal injuries result in significant time loss and limitations for these athletes.2-4 The overall injury rates for volleyball have been calculated as 4.58 per 1000 hours of matches played and 4.10 per 1000 hours of practice.1 The overall injury rate for women's volleyball athletes is 7.48 per 1000 athlete exposures.5 The top three most common musculoskeletal injuries reported in women's collegiate volleyball are ankle sprains, knee internal derangements, and shoulder muscle-tendon strains.1,5

The overuse injury incidence rate for volleyball has been estimated at 0.6 per 1000 hours of participation.4 This is an underestimate because overuse injuries are often under-reported due to most studies defining injuries as events involving time loss.6 Baugh et al. calculated the non-time-loss injury rate in collegiate women's volleyball as 4.24 per 1000 athletic exposures.5 Previous research indicates that shoulder overuse injuries account for 16-32% of all volleyball overuse injuries.4,7 Even athletes who are not experiencing time loss may be experiencing limitations. In a survey of 2,352 volleyball athletes, 46% reported shoulder pain interfered with their ability to play.2 Seventy-seven percent of 30 surveyed volleyball attackers reported that their shoulder pain limited where they could place the attack shot on the court.3

The pitching motion used in baseball is well documented to contribute to overuse injuries when performed in excess.8-10 The overhead swing motion utilized by volleyball athletes to attack and serve the ball is thought to have a similar relationship to injury because of biomechanical similarities to the baseball pitching motion.11-15 Both the baseball pitch and volleyball swing place high demands on shoulder musculature.11 Maximal internal rotation velocity is similar between the two motions with baseball players reaching velocities between 6000-7000°/sec compared to volleyball swings reaching 4520±1020°/sec.12,15 Maximal internal torques during volleyball serve (40Nm) are approximately two-thirds that of pitching (67Nm).12,14 If these mechanical demands are part of the cause of the high incidence of shoulder injuries in baseball and volleyball, the volumes of overhead arm swings may be another aspect of this explanation.

The concept of overuse injuries requires that first typical use must be defined. In youth baseball, research has demonstrated that pitching volumes exceeding 75 pitches in a single game increase the risk of injury to the upper extremity.9 While the mechanics of the volleyball swing are known to be comparable to those of a baseball pitching, the volumes of volleyball swings, have not been extensively studied.

Two previous studies have examined swing volume in volleyball athletes. Hurd et al.16 counted the number of swings that occurred over the course of seven seasons using match statistics from a single Division I collegiate women's volleyball team. The number of swings varied by position but ranged between 5-7 swings per game per player. Mayers et al.,17 estimated the total number of attacks and serves performed by an entire team during a match to be approximately 200 overhead swings using match statistics from multiple collegiate teams. Mayers et al.17 also estimated practice volumes collected during a single practice session. While these studies provide insight into the number of swings volleyball players are exposed to over the course of a season, they are primarily based primarily on match statistics and do not track musculoskeletal injuries. Further, a single practice to estimate what happens over the course of a season is unlikely to provide an adequate estimate of practice hit and serve volumes.

Therefore, to better understand the typical volume of overhead swings and injuries reported over the course of a volleyball season, a two-year prospective cohort study to record these events during both practices and matches in a single Division I collegiate women's volleyball team was performed. The purpose of the current study is to provide a complete depiction of typical overhead swings, serves, and hits, which occur in both practices and matches. The primary hypothesis was that significantly more swings would occur in practices compared to matches. The secondary hypothesis was that greater swing volume and greater shoulder related musculoskeletal injury frequency would occur in the preseason than the season. A consistent occurrence or
concordant behavior between these two variables may suggest they could be related.

METHODS

Participants
Each participant read and signed a university IRB approved consent form prior to data collection. Inclusion criteria for this study consisted of being a member of the University of Kentucky Division I women’s volleyball team. No participant asked to be excluded from the study; therefore, we collected swing and serve counts from 19 athletes over a two-year window. Seven players were outside hitters, four were middle blockers, five were defensive specialists, and three were setters. Eight of the 19 athletes participated in both years of data collection. Participants were 19 ± 1 years old, 1.8 ± .08m tall and weighed 73.47 ± 9.43kg.

Data Collection
Each participant’s position, number of hits, number of serves, and participation status were recorded daily for two seasons. Data were collected from practices and matches during the fall 2014 and 2015 seasons. Participant position was determined using the team’s online roster. Researchers attended or watched a digital video of practices and matches and counted each time every player hit or served the ball. Warm-up prior to matches were included in this study. The number of total swings was calculated by summing the hit and serve values.

A serve was recorded any time a participant initiated play by hitting the ball using an overhead motion from the end-line. A hit was recorded any other time a participant used a forceful overhead arm swing attempting to move the ball over the net; in previous studies, hits have been defined as “attacks” or spikes but are the same arm motion that is described as hits in this study. The sum of hits and serves was also recorded and was labeled “swings.” The researcher’s reliability for counting each type of overhead swing was assessed by watching five of the recorded events a second time. The counts from this second trial were compared to the same events counts recorded during the data collection period to determine the intraclass correlation coefficient (ICC). Serve ICC was .988 (CI .985, .991) with a standard error of measurement = 0.52, hit ICC was .986 (CI .983, .991) with a standard error of measurement = 1.64, and total swings ICC was .989 (CI .982, .993) with a standard error of measurement = 1.80.

Volleyball activities were documented daily. Volleyball activities included matches, practices, and off-days. A match event was identified when the team participated in match competition. A match included all of the sets played in a single match. Practice was recorded when the team completed a mandatory, full-team practice. Rest-day was recorded any time when there was no practice or match. On some days, two volleyball activities would occur, either two practices, two matches, or practice and match. During each volleyball activity, the serve and hit data were recorded separately by player and event. Matches were accounted for using the team’s schedule. All other days were counted as practices unless the staff athletic trainer indicated it was a rest day.

The athlete’s injury status was recorded by the team’s certified athletic trainer for every event. Standard practice was to categorize injury status into four conditions: full participation, full participation but athlete reported some issue was occurring, limited participation due to injury, no participation due to injury. These four categories were further collapsed into two categories: full participation (combined the two full categories) or limited participation (combined limited and no participation categories) for statistical analysis of shoulder related injuries. Event and participation status were confirmed by the team’s athletic trainer to assure the data was accurately recorded. An attempt was made to capture all events, but this was not always possible due to practice times being changed, video recording not available, and the research team member not available to capture data.

Data Analysis
The volume of serves, attacks, and swings for the two seasons were the dependent measures and averaged for the two independent variables of events and position. Event had two levels: practice and matches. Position had four levels: middle blocker, outside hitter, defensive specialist, and setter. Three separate 4x2 univariate ANOVAs were completed, one for each dependent variable. Significance value was set
at \( p \leq 0.05 \). Bonferroni post-hoc analysis compared pairwise differences between dependent variables with significance set at \( p < 0.05 \) when appropriate. Data were analyzed using SPSS version 22 (IBM, Armonk, NY).

To investigate the relationship between musculoskeletal injuries and swing volume the following steps were undertaken. First, average swings per session were used for statistical analysis as it summed both hits and serves into one value that was averaged across all positions. The season was broken up into two components; pre-season and competitive season. Pre-season accounted for two weeks of practice for both years and included all practices and inter-squad scrimmages prior to competitions against other teams. The season averaged 17 weeks for both years and included all practices, non-conference, conference, and tournament competitions. Next, a one way ANOVA was performed to determine if the mean number of swings per session was different between the pre-season and the season. Next, a Pearson Chi-Square test was used to determine if the proportion of shoulder injury status differed between seasons. Injury status was defined as full participation (full participation + full participation but athlete reported some issue was occurring) or limited participation (limited participation due to injury + no participation due to injury). Season had two levels pre-season or season. All analysis was set with significance set at \( p < 0.05 \) using JMP version 12, SAS Institute, Cary, NC.

Results

Researchers captured data from approximately 75% of all volleyball activities across two seasons (Table 1). Practice events make up the majority of these missed events due to scheduling changes and conflicts between members of the research team available to collect the video recording of the practice. These missed practices occurred throughout the year missing 1-2 practices per week with the highest number of missing occurring in the early part of the first year due to scheduling conflicts. Excluding off-days and non-shoulder injuries, 222 volleyball activities occurred during the study period; 65 (29%) activities were matches, and 157 (71%) activities were practices accounting for a total of 2098 athletic exposures. The duration of matches averaged 110 ± 27 minutes which was similar to practice (121 ± 37 minutes) supporting that average data could be compared statistically without risk of duration bias.

Descriptive statistics for serves by event and position are presented as means and standard deviations in Table 2. An ANOVA for serves revealed no significant interaction for events by position (\( p=0.13 \)) There was a main effect for event, indicating on average, more serves occurred during practice 23 (CI95 22, 24) than during matches 10 (CI95 9, 11) regardless of player position (\( p < 0.001 \)). The ANOVA for serves also revealed a main effect for position (\( p < 0.001 \)), Bonferroni post-hoc analysis revealed that middle blockers serve less than all other positions and that outside hitters' served less than defensive specialists regardless of the event. (Figure 1).

Descriptive statistics for hits are presented as means and standard deviations by position and event in Table 2. An ANOVA for hits resulted in an interaction for event by position (\( p<0.01 \)). Bonferroni post-hoc analysis revealed that setters, middle blockers, and defensive specialists performed significantly more hits during practice than during matches. Only outside hitters performed the same number of overhead hits in matches as in practice. (Figure 2).

<table>
<thead>
<tr>
<th>Event</th>
<th>Captured (%)</th>
<th>Not Captured (%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Game</td>
<td>54 (83.1)</td>
<td>11 (16.9)</td>
<td>65</td>
</tr>
<tr>
<td>Practice</td>
<td>112 (71.3)</td>
<td>45 (28.7)</td>
<td>157</td>
</tr>
<tr>
<td>Total</td>
<td>166 (74.8)</td>
<td>56 (25.2)</td>
<td>222</td>
</tr>
</tbody>
</table>

Captured-Data was collected for the event, Not Captured-No data was collected for the event

<table>
<thead>
<tr>
<th>Position</th>
<th>Event (SD)</th>
<th>Serves (SD)</th>
<th>Hits (SD)</th>
<th>Swings (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Practice</td>
<td>23 (18)</td>
<td>14 (13)</td>
<td>57 (24)</td>
</tr>
<tr>
<td>Game</td>
<td>12 (8)</td>
<td>7 (10)</td>
<td>19 (13)</td>
<td></td>
</tr>
<tr>
<td>OH</td>
<td>Practice</td>
<td>21 (19)</td>
<td>29 (20)</td>
<td>50 (33)</td>
</tr>
<tr>
<td>Game</td>
<td>10 (10)</td>
<td>27 (19)</td>
<td>37 (26)</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>Practice</td>
<td>19 (14)</td>
<td>29 (20)</td>
<td>48 (27)</td>
</tr>
<tr>
<td>Game</td>
<td>7 (8)</td>
<td>16 (13)</td>
<td>22 (16)</td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>Practice</td>
<td>27 (23)</td>
<td>12 (12)</td>
<td>40 (28)</td>
</tr>
<tr>
<td>Game</td>
<td>12 (10)</td>
<td>8 (11)</td>
<td>20 (14)</td>
<td></td>
</tr>
</tbody>
</table>

S- Setter, OH-Outside Hitter, MB-Middle Blocker, DS-Defensive Specialist

Serves-mean number of serves completed per event, Hits-mean number of overhead hits completed per event, Swings is the sum of servers and hits occurring during an event-mean number of swings completed per event, SD-standard deviation
Descriptive statistics for swings (serves + hits) are presented as means and standard deviations by position and event in Table 2. The ANOVA model resulted in interaction for the event by position (p = .002). Bonferroni post-hoc analyses identified that in each position an average of 19 more swings occurred in practice compared to matches. (p < .01, Figure 3). The volleyball players averaged nearly twice as many swings in practice as in matches.

Pre-season average swings per session 47.1 (CI 95 44.1, 50.1) was significantly greater than average swings per session during the competitive season 37.7 (CI 95 36.4, 38.9) (p < 0.001) resulting in a mean difference of 9.4 (CI 95 6.1, 12.7) swings. There were 2098 total athletic exposures across both pre-season and season for the two years. The certified athletic trainer recorded 36 exposures in which the players were either limited or not able to participate due to a shoulder related musculoskeletal injury for the entire season. The Chi-square test for independence revealed that the proportion of injury status differed significantly between pre-season and competitive season (p < 0.027) with a significantly greater probability of being in the limited participation category during the pre-season (2.9%) than during the season (1.1%) (Table 3).

DISCUSSION

The primary purpose of this study was to provide a comprehensive understanding of collegiate women's volleyball players' workload by quantifying the number of swings performed in a season. Particular
attention was given to practice swing volume, as it has not been previously recorded in this level of detail. The frequency of time loss and non-time loss injuries was greater during the pre-season over the regular competitive season which follows a concordant pattern of total swing volume being greater in the pre-season than the competitive season. These findings bring attention to a characteristic pattern of two variables that have been found to be related in other studies, but this study design does not allow a direct relationship between cause and effect to be determined.

The results revealed that significantly more swings occur in practice than in matches. Match swing volumes from the current study agree with match volumes previously reported in the literature. The current study agrees with previous research that during a typical match, overhead swing volume will range between 20-40 swings per match dependent on position. The current study supports the volume of serves and hits recommended in the interval hitting program developed by Hurd et al. Although this interval program was developed using only match counts, the values utilized in the program align reasonably well with the current study’s findings when taking into consideration the total number of overhead motions, both serves and hits combined. There was about a 10 swing difference which is primarily accounted for by the current study using practice data to compare to Hurd’s match data. In the current study, there was an observed difference of 19 more swings in practice compared to matches which likely accounts for the differences. The direct comparison for outside hitters revealed 19 hits in Hurd’s interval program compared to the current study but this offset as 28 more serves were recorded in the current study resulting in only nine total swing differences. The return to play protocol would still sufficiently prepare athletes for returning safely to both practice and match demands (Table 4). These two studies were completed on different teams with

<table>
<thead>
<tr>
<th>Position</th>
<th>Swing Type</th>
<th>Hurd et al. (^{16}) RTP Volume</th>
<th>Current Study Practice Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>Serves</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Hits</td>
<td>32</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>52</td>
<td>61</td>
</tr>
<tr>
<td>OH</td>
<td>Serves</td>
<td>20</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Hits</td>
<td>48</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>68</td>
<td>77</td>
</tr>
<tr>
<td>S</td>
<td>Serves</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Hits</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>40</td>
<td>30</td>
</tr>
</tbody>
</table>

Hurd et al. \(^{16}\) in Table 2 of their publication describe the number of swings by type, serves or hits in the final step of a proposed return to play (RTP) program. Current Study Practice Volume-mean volume per player in a typical practice from the current study’s data, MB-middle blocker, OH-outside hitter, S-setter. Hurd et al. \(^{16}\) did not have a middle blocker categorization but for comparison their data from middle attacker was used.

| Table 3. Proportion of Injury Status (Full or Limited Participation) by Season. |
|---------------------------------|-------------------------------|-------------------------------|
| Pre-Season                      | Counts*                       | Limited Participation        | Total Events                  |
|                                 | % of Row                      |                               |                               |
| Counts*                         | 409                            | 12                            | 421                           |
| % of Row                        | 97.15                          | 2.85                          | 100                           |
| Competitive Season              | Counts*                       | 1653                          | 24                            | 1677                           |
| % of Row                        | 98.57                          | 1.1                           | 100                           |

% = Percentage
% of Row represents the athletic exposure count as percentage of the row total. The events, practices and games are combined across the two years of data collection to accounts for the 2008 events.

*Counts represent the number of athletic exposures for each level of participation.
different coaches and years apart from each other but yielded similar results suggesting that these are relatively consistent swing volumes for women's collegiate volleyball.

The total seasonal volume of hits and serves were higher in the current study compared to previous values reported by Mayers. They reported an average of 4,346 ± 585 hits and 2,824 ± 468 serves that occurred during matches in a typical 12 week season. These data were accumulated across all positions. Analysis of the current study's data across all positions averaged across the two seasons revealed 1500 more hits and 670 serves than previously reported. The differing values may be due to coaching and playing styles or season length; it is most likely due to the method of data collection used in each study. The current study involved a researcher counting the number of overhead swings while the previous study used match statistic estimates to determine the number of overhead swings. The current study contributes new knowledge that a women's collegiate athlete will perform 35-50 swings per practice dependent on position during a typical 30 + match season.

The second aim of the current study was to investigate the potential relationship between swing volume and shoulder related musculoskeletal injuries. Although the current study is limited to a single team over two seasons, there appears to be a pattern and potential relationship between swing volume and musculoskeletal injury status with a higher proportion of reported injury, limited participation or complete removal from participation occurring in the pre-season during the first two weeks of both seasons. These findings agree with previous research; Baugh et al., reported the injury rate during women's volleyball pre-season was nearly double the regular season injury rate (10.43 vs. 5.99 per 1000 athletic exposures). These findings need to be brought to coaches' attention mainly due to the high incidence of reported shoulder pain in volleyball players. Cause and effect cannot be established with a single study; however, the high pre-season swing volume may be a contributing factor to the pre-season injury incidence.

In order to further investigate the relationship between season and injury, a Chi-Square analysis was performed. A Chi-Square analysis tests the independence of the variables, in this study these were two categorical variables season and injury status. In this study, the statistical analysis compared the proportion of injury status across the two components of the season. The results indicated that these two variables are not independent, as there was a significant finding indicating that the two variables had some dependence on each other. It is important to remember that this analysis does not enable the research to determine cause and effect. The data indicates that there are proportionally more reported injuries during the pre-season than during the competitive season. Further, athletes completed an average number of 47 swings (serves + hits) in the pre-season compared to 37 swings during the regular competitive season. This would suggest that the workload on the athlete was higher in the pre-season. The large volume of practices occurring during the pre-season likely accounts for the high average swing volume. These data would suggest that there appears to be some type of relationship between swing volume and reported musculoskeletal injury but cannot establish a true relationship. This study was undertaken to investigate the potential that the relationship exists. It provides preliminary evidence that a more extensive research project should be undertaken to determine if a true relationship between swing volume and injury status are related in collegiate volleyball as has been done in youth baseball.

Similar patterns of workload and injuries have been noted in rugby where the workload was measured in the distance covered via GPS systems. Studies of workloads in rugby have shown that reducing pre-season training volumes resulted in reduced injury rates while still adequately preparing athletes for the demand of a season. While the demands of volleyball and rugby are very different, it may be useful to examine reducing pre-season swing volumes to see if there is a reduction in injury.

The current study is unique because arm swings were visually counted during practices and matches rather than gathered only from matches or estimated from a single practice observation. Utilizing the team's athletic trainer to track both time-loss and non-time-loss injuries add clinical relevance to this
study. Overuse injuries can be debilitating and lead to time loss injuries\textsuperscript{4,7} but are more commonly managed by modifying activities or limiting drills rather than removing the athlete from play. The nearly 2% increase proportion of players participating as limited status during the pre-season compared to the season may be a result of workload or potentially the single athletic trainer protecting the athlete for the upcoming season. Since only one team was used in this study, the external validity is limited. However, high workload volumes in overhead sports have been observed to result in greater likelihood of upper extremity overuse injuries when acute increases in workload occurred.\textsuperscript{22,23} This is what was observed in the current study, during pre-season volleyball training.

Volleyball is one sport where the injury rate in practice is nearly the same as it is in competitions.\textsuperscript{1} However, the swing workload volumes occurring during practice are rarely taken into consideration when accounting for overhead motions and could explain the practice injury rate to approach the match injury rate. This study was unique, as swing volume during practice was included and revealed that across nearly all positions double the number of swings were occurring during practice. As practices and matches both averaged two hours long this increase in volume is not accounted for with an increase in time. The additional focus on practice data in the current study was critical to capture an accurate assessment of overhead motions occurring to collegiate volleyball athletes.

LIMITATIONS
The present study has limitations. Only one NCAA Division I team was observed in this study; therefore, the results may not apply to teams at other levels due to different coaching and playing styles. However, the swing volumes were similar to those collected from another Division I team. Researchers made every attempt to record all events over the course of the season, but 25% of events were unable to be recorded, which were primarily practices. The missing events does not have a substantial impact on the results as the data was averaged on 112 out of 154 potential practices over the course of two years were recorded in this data set. However, to the authors’ knowledge, the current study represents the most complete swing volume estimate to date. The decision to limit or allow full participation was based on a single athletic trainer which may bias the result of this study on one team and potentially limit the external validity of this study. The dependence between season and injury status only suggest a relationship may exist between the increased workload during the pre-season and competitive season. A more extensive study examining the direct relationship between swing volume and injury history that incorporates a variety of coaching styles would be necessary to establish if a relationship exists between swing volume and musculoskeletal injury occurrence.

CONCLUSIONS
Women volleyball athletes perform approximately twice as many overhead swings in practices than in matches. Coaches and health care providers need to consider swing volume beyond those occurring during matches as this underestimates actual swing volume for an athlete. The volume found in this study can be considered the best estimate to date of overhead swing volume in Division I collegiate women’s volleyball teams. There appears to be a proportionally higher volume of non-time loss injuries during the pre-season. Coaches and health care providers can potentially use this finding to coordinate their training volume better to potentially reduce musculoskeletal injuries. Further research is needed to examine if overtraining causes injury.

REFERENCES


ABSTRACT

**Background:** Excessive baseball pitch volume has been associated with increased risk of injury in adolescents. However, many collegiate athletes report non-time loss injuries over the course of the season. It is unknown how pitch volume throughout a collegiate baseball season affects arm soreness.

**Purpose:** The primary purpose of this study was to determine the relationship between pitch volume and self-reported arm soreness. A secondary purpose was to determine the relationship between change in pitch volume and change in arm soreness over the course of the season for collegiate baseball pitchers.

**Study Design:** Prospective Cohort

**Methods:** Seven collegiate baseball pitchers volunteered to participate in a yearlong prospective study. The seven pitchers reported daily pitch volume and level of soreness from the fall through spring collegiate baseball season during practices and games. The athletic trainer, a member of the research team, tracked athletic exposures and injuries for the entire season. Frequency counts of athletic exposures were categorized by game, practice, conditioning and injury status. Frequency counts of pitch volume was categorized by game, game bullpen, practice bullpen, flat ground, long toss and warm-up pitches. The pitch volume and soreness levels for each athlete were used to determine the relationship between these two variables using a Pearson correlation.

**Results:** The seven pitchers were involved with 1,256 athletic exposures and a total of 54,151 throws, averaging 7,735 throws per player for the entire season. The pitch volume and self-reported arm soreness for the entire season revealed a correlation of $r = .72$ ($p = .004$). The relationship between change in pitch volume and change in arm soreness was $r = .635$ ($p = .001$) over the season.

**Conclusion:** There was a moderate significant correlation between arm soreness and pitch volume across the whole season. This relationship was maintained when evaluating weekly changes.

**Level of Evidence:** 4

**Keywords:** acute workload, non-time loss injury, overhead throwing, pitch counts
INTRODUCTION
The incidence of injury in college baseball practices and games is 1.85 injuries/1000 athlete-exposures and 5.78 injuries/1000 athlete-exposures, respectively. Self-reported episodes of pain are quite frequent in baseball. In a youth baseball survey, nearly 50% of pitchers over the course of a season reported shoulder or elbow pain. The majority (70%) of these complaints were recorded as mild, defined as pain in the elbow or shoulder joint without loss of league-sanctioned games or practice time. A recent report stated that of all injuries reported to an athletic trainer in collegiate baseball 59.1% are non-time loss injuries. Muscular soreness and pain are often associated with these “non-time loss injuries.”

The relationship between pitch volume and upper extremity injury has been established for adolescent pitchers focusing on time-loss injuries. Time-loss injuries are defined as any injury requiring removal from the current session, missing a day of practice or competition which may require physician referral or diagnostic procedures. However, baseball pitchers also experience injuries which do not result in time-loss. These injuries are classified as “non-time loss injuries” and are defined as any injury evaluated by the athletic trainer that did not necessitate removal from game or practice but required intervention or practice modification.

A report of discomfort or soreness from athletic activity is a physiological response from exercises or may indicate a subclinical adaptation of an injury that is occurring. An excessive amount of soreness from physical activity is termed delayed onset muscle soreness. Studies have suggested that soreness is also a moderate indicator of a level of fatigue and developing overload on the musculotendinous tissue. Recently, attention has focused on acute changes in workload can increase the likelihood of an injury. To date, the relative change in throwing volume to arm soreness in collegiate baseball players has not been reported. Therefore, this study evaluated if the level of soreness was related to throwing volume in collegiate pitchers. The primary purpose of this study was to determine the relationship between pitch volume and self-reported arm soreness. A secondary purpose was to determine the relationship between change in pitch volume and change in arm soreness over the course of the season for collegiate baseball pitchers.

METHODS
Participants
The study was a longitudinal observational study carried out over the fall and spring season of 2009-2010. The participants consisted of seven division I collegiate baseball pitchers from a single team in the Southeastern Conference. Participants were on average 20 ± 1 years old, weighed 90 ± 8.6 kg, and height 191 ± 7 cm. Two of these pitchers are categorized as starters, and five of these pitchers are categorized as relievers determined by their coaching staff for the spring season of 2010. One of the pitchers did not join the study until week two of the fall season. Inclusion criteria consisted of being a collegiate baseball pitcher for the University of Kentucky. The only exclusion criterion was if the athlete was injured and unable to participate at the beginning of the study. All testing and data collection were performed in a collegiate athletic training room. All participants volunteered for this study and signed approved informed consent forms (UK IRB #09-0545) before commencement.

Exposures
Three key variables were collected in this study: athletic exposure, self-reported soreness and self-reported pitch count. The pitcher’s exposure was categorized into one of six categories based on what the individual athlete and team did for each day through the fall and spring seasons. “Injured-out” category indicated that athlete was unable to participate due to an injury or illness. “Injured-conditioning” indicating that the athlete could condition but not participate in practice or game. “Injured-practice only” indicates that the athlete was modified during practice due to an injury or illness. “Conditioning only” indicates that the team was only conditioning that day, but the athlete was able to participate in all conditioning activities. “Days off” indicate days of mandatory rest or recommended by the coaching staff. “Practice” indicated team practices that the athlete performed fully. During the fall season, a “Game” exposure was an inter-squad scrimmage and during the spring indicated a competition during an opposing team. The fall season consisted of 13 weeks and
the spring season consisted of 20 weeks. The winter break between semesters was not included in this data.

Soreness
Soreness was recorded by the athlete using a 0-10 numeric rating scale comparable to a pain scale at the end of the practice or workout on a numeric scale with 0 = no soreness and 10 = constant soreness in the arm that affects sleep. There were three contextual levels of soreness that were reported: soreness at rest, soreness with baseball activity and soreness with non-baseball activity. Daily soreness was totaled from the three questions and recorded into the excel database for each athlete individually. Soreness can arise from any source such as, bone, ligament, fascia or muscle which can potentially reduce muscle function. Previous research has demonstrated that elevated plasma creatine kinase (CK) levels are related to muscle damage. Recent studies have shown that as creatine kinase increases due to activity, muscle soreness and fatigue increases that can directly affect performance.

Pitch Volume
To acquire pitch volume data during practice, each participant provided estimated pitch counts for each category of throwing activity. Pitch counts were divided into six different throwing activities: catch, long toss, flat ground, practice bullpen (on practice days), game bullpen (game day bullpen pitches), and game pitching. Catch was typically performed at 30-50% intensity at a distance of approximately 70 feet apart. Long toss was greater intensity at distances ranging from 120-150 feet with the intention to get the ball to the partner on the fly or on one hop. Flat ground pitching intensity varied at a distance of 60 feet. Bullpen during practice focus varied based on the day and athlete based on coaching instructions but was performed on a pitching mound. At the end of every day on the same sheet of paper the athlete recorded soreness, they estimated their pitch volume for each activity. The data were entered into an excel spreadsheet for each athlete each day. Game day bullpen followed the typical format to prepare the athlete to pitch in the game. The coaching staff and team recorded game and bullpen pitches as part of the typical records kept. This data was not estimated by the athlete, but recorded directly from the team records into the excel database. This data was collected daily using a simple paper data collection form which each participant completed immediately after each practice or game. Pilot testing revealed that athletes were within approximately 15% of their estimated values when compared to actual counts made by the research team. Self-reporting pitching volume is a limitation of the study but was the only way available at the time of the study to capture pitch volume.

Statistical Analysis
Athletic exposures were summed for all pitchers for each category described above with counts and percentages calculated for fall, spring and total season. Pitch counts for all pitchers for each type were summed with counts and percentages calculated for fall, spring, and total season. The total pitches and total soreness for each player for the entire season were used to determine the relationship between pitch count total volume and total soreness. Three separate correlations were performed for the fall, spring and total season to determine the degree of relationship between pitch volume and soreness. Measuring workloads on an athlete can occur by monitoring external workload such as distance running or in this study pitch volume. Internal workload can be assessed by monitoring physiological or psychological stressors such as heart rate or rating of perceived exertion. Integrating these two measures of workload is often recommended to monitor changes in workload to assess the likelihood of injury in sports. However, external workload alone has been used to predict future injuries. It was not the intention of this study to predict injury but to determine how external workload of pitch volume during practice and games effect shoulder soreness. The weekly pitch volume and soreness volume had to be determined. The total pitches thrown by an individual pitcher for each week were determined by summing pitch volumes by week. Soreness scores were summed together from the three questions for each week for each player. For example, if an athlete reported a score of 2 for soreness at rest, a score of 5 soreness with baseball activity and a score of 3 soreness with non-baseball activity his total score for a day would 10 out of 30. The individual player’s daily
pitch counts and soreness scores were summed together to create a total number of pitches and soreness for each week. One of the pitchers did not start recording data until week three of the fall season. Therefore, the change scores for all subjects did not include the first two weeks of the fall season. The acute to chronic workload ratio of 1:4 has been used previously to investigate the relationship between external workload and increased risk of injury. However, due to the relatively short fall season, the ratio 1:3 was used to investigate how a change in pitch volume correlated with change in soreness reported by the athletes. The acute to chronic external workload of pitch volume is calculated by dividing the current week pitch count volume (e.g., 300) divided by the average of the three previous weeks pitch volume (e.g., 150, 200, 250 equals an average of 200). This example would result in an equation of 300/200 = 1.5 acute to chronic pitch volume workload. A value greater than 1.0 indicates an increase in the acute workload of pitch counts. This is considered a negative training balance as the previous chronic training volume is below the acute workload for the current week. A value less than 1 indicated a decrease in acute workload indicating a positive training balance as the previous chronic training volume is above the acute workload for the current week. A value of 1 indicates workload for the week remained the same as the average of the previous three weeks. A negative training balance has been associated with an increased risk of injury in cricket players. The acute to chronic external workload calculation was repeated for each subsequent week for the fall season starting in the sixth week as the first two weeks were ignored as all subjects were not enrolled. This same calculation was performed for soreness. In the spring season, the same calculations were carried out starting in the fourth week of the spring season for pitch count and soreness.

RESULTS

Exposures

Athletic exposures by category are detailed in Table 1. The frequency counts of athletic exposures revealed that the majority of the exposures occur during practice regardless of the season accounting for 43% of the exposures. Days off or rest days accounted for the second most prevalent exposure which is mandated by the rules of college baseball. Sixty-four days or 4% of the total 1653 athletic exposures were missed practices or games. The non-time loss categories in which athletes were modified in practice or participating in conditioning accounted 206 days or 12% of the total exposures. The majority of these occurred during the fall season when athletes are not in the competitive season. During the spring season, only 12% of the athletic exposures of these seven pitchers were during a game situation. (Table 1)

Pitch Volume

The cumulative pitch volume for the seven pitchers is summed together and presented by type and season. (Table 2) There were a total of 54,151 pitches

<table>
<thead>
<tr>
<th>Table 1. Exposures during fall, spring and total season by category.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Fall</td>
</tr>
<tr>
<td>Athletic</td>
</tr>
<tr>
<td>% of exposure</td>
</tr>
<tr>
<td>Spring</td>
</tr>
<tr>
<td>Athletic</td>
</tr>
<tr>
<td>% of exposure</td>
</tr>
<tr>
<td>Total Season</td>
</tr>
<tr>
<td>Athletic</td>
</tr>
<tr>
<td>% of exposure</td>
</tr>
<tr>
<td>Cond. = Conditioning</td>
</tr>
</tbody>
</table>

The International Journal of Sports Physical Therapy | Volume 14, Number 1 | February 2019 | Page 100
thrown by the seven participants representing an average of 7,735 throws per player for the entire college baseball season. Forty-five percent of all the pitches thrown were relative low intensity as they were in the “catch” category. A particularly interesting finding is that game pitches only accounted for 12% of all pitches during the spring season. Practice bullpen pitches equaled the game pitches during the competitive spring season but are usually not accounted for in the total volume of pitches thrown. Game day bullpens and game pitches during the spring season accounted for a total of 7554 across the seven pitchers. Bullpen pitches on game day accounted for 2961 (39%) of the total pitches thrown by these seven athletes. (Table 2)

**Correlations**

The pitch count and soreness data were examined for normality with a Q-Q plot in SPSS version 22. The data were found to be normally distributed and were confirmed with a Shapiro-Wilk test (p > 0.169). Pearson correlation between total pitch volume and soreness for the fall revealed a non-significant correlation of \( r = -0.16 \) (\( R^2 = 0.026, p = 0.73, \) Figure 1). The Pearson correlation for the same two variables in the spring season revealed a correlation of \( r = 0.86 \) (\( R^2 = 0.75, p = 0.012, \) Figure 1). When taking into account the entire season spanning the fall and spring the Pearson correlation between pitch counts and soreness was \( r = .72 \) (\( R^2 = 0.52, p = .004, \) Figure 2). The one week acute to chronic (three-week average) workload for pitch count and soreness is presented in Table 3. The Pearson correlation between the acute: chronic workload ratio for pitch count and soreness was \( r = 0.64 \) (\( R^2 = 0.40, p = 0.001 \))

**DISCUSSION**

The primary purpose of this study was to evaluate the relationship between pitch volume and self-reported arm soreness over the course of a collegiate baseball season. Previous literature in adolescent pitchers shows that there is a relationship between pitch volume and injury. However, this is the first study to investigate the relationship between pitch volume and shoulder soreness among collegiate baseball pitchers. When examining the data for the fall, there was not a meaningful correlation between pitch volume and soreness. This is likely due to the fall being the off-season and throwing volume was the lowest for the whole year. The lower volume of throwing is due to less practice exposures (198/712 = 28%) and increased number of days in which athletes were out of completion (39/64 = 61%) or on limited participation (73/88 = 82%). (Table 1) The spring season, which is the competitive season accounting for 72% of all practices and 75% of games generated a significant correlation (\( r = 0.82 \)) between pitch volume and soreness. This correlation remained moderately

**Table 2. Total pitch volume for fall, spring, and total season by pitch type.**

<table>
<thead>
<tr>
<th></th>
<th>Fall</th>
<th>Spring</th>
<th>Total season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Pitch Counts</td>
<td>7605</td>
<td>16900</td>
<td>24505</td>
</tr>
<tr>
<td>% of all throws</td>
<td>46%</td>
<td>45%</td>
<td>45%</td>
</tr>
<tr>
<td>Game Bullpen</td>
<td>2208</td>
<td>4777</td>
<td>6985</td>
</tr>
<tr>
<td>% of throws</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>for entire season</td>
<td>5%</td>
<td>8%</td>
<td>7%</td>
</tr>
<tr>
<td>Game</td>
<td>900</td>
<td>2961</td>
<td>3861</td>
</tr>
</tbody>
</table>

% = percentage
Catch represents warm up throws, typically performed at 30-50% intensity at a distance of approximately 70 feet apart.
strong ($r=0.72$) when combining the fall and spring seasons. It is clear that the spring season is accounting for the strong correlation between pitch volume and soreness for the entire season is due to the greater variability in both pitch volume and soreness levels.

This moderately strong relationship is not surprising based on anecdotal evidence reported by clinicians treating these athletes. However, this study demonstrates that spikes in soreness appear to be moderately related ($r=.64$) to spikes in pitching volume. Recent literature has indicated that over half (59%) of baseball injuries are non-time loss. Arm soreness is a common ailment treated by clinicians. Tracking changes in throwing volumes throughout the season not just during games may provide valuable insight.

Figure 1. *Correlation of pitch counts and soreness for the fall and spring*. Gray color represents fall and black color represents spring season.

- Subject 1
- Subject 2
- Subject 3
- Subject 4
- Subject 5
- Subject 6
- Subject 7

Figure 2. *Correlation of acute:chronic workload for pitch count and soreness for the entire season*. Acute represents the sum of pitches or total soreness for the current week. Chronic represents the average number of pitches per week or average total soreness per week for the previous three weeks.
in minimizing arm soreness and may potentially reduce overuse injuries.

In previous youth baseball studies, pitch volume has been recorded utilizing pitch count logs, which were completed by coaches after each game and only reported game pitches. This research led to a demonstration of high pitch counts exposing athletes to a higher risk of injury and generating pitch count limits in youth baseball. In this setting of only seven collegiate baseball pitchers, it was not feasible to investigate the risk of injury. Therefore, this study focused on what is commonly managed in the athletic training room, which is soreness. Shoulder soreness in baseball pitchers is an indication of subclinical adaptation in response to a load placed on the shoulder.

The external workload of pitching was based on previous pitch volume research. Self-reported daily

<table>
<thead>
<tr>
<th>Season</th>
<th>Week</th>
<th>Total Pitches</th>
<th>Total Soreness</th>
<th>Acute: Chronic Pitch Workload (1:3)</th>
<th>Acute: Chronic Soreness Workload (1:3)</th>
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<tr>
<td>Fall</td>
<td>1</td>
<td>145</td>
<td>47 NC</td>
<td>NC</td>
<td>NC</td>
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<tr>
<td></td>
<td>2</td>
<td>357</td>
<td>69 NC</td>
<td>NC</td>
<td>NC</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1317</td>
<td>73 -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1217</td>
<td>97 -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1600</td>
<td>88 -</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>6</td>
<td>1628</td>
<td>104 1.18</td>
<td>1.21</td>
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<tr>
<td></td>
<td>7</td>
<td>1634</td>
<td>104 1.10</td>
<td>1.08</td>
<td></td>
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<tr>
<td></td>
<td>8</td>
<td>1715</td>
<td>121 1.06</td>
<td>1.23</td>
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<tr>
<td></td>
<td>9</td>
<td>1537</td>
<td>91 0.93</td>
<td>0.83</td>
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<tr>
<td></td>
<td>10</td>
<td>1883</td>
<td>98 1.16</td>
<td>0.93</td>
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<tr>
<td></td>
<td>11</td>
<td>1829</td>
<td>113 1.07</td>
<td>1.09</td>
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<tr>
<td></td>
<td>12</td>
<td>685</td>
<td>67 0.39</td>
<td>0.67</td>
<td></td>
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<tr>
<td></td>
<td>13</td>
<td>835</td>
<td>44 0.57</td>
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<tr>
<td>Spring</td>
<td>1</td>
<td>1055</td>
<td>103 -</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>2</td>
<td>1542</td>
<td>146 -</td>
<td>-</td>
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<tr>
<td></td>
<td>3</td>
<td>1805</td>
<td>127 -</td>
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<td>4</td>
<td>2070</td>
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<td></td>
<td>5</td>
<td>2110</td>
<td>87 1.17</td>
<td>0.64</td>
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<tr>
<td></td>
<td>6</td>
<td>2328</td>
<td>97 1.17</td>
<td>0.87</td>
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<td></td>
<td>7</td>
<td>1949</td>
<td>90 0.90</td>
<td>0.84</td>
<td></td>
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<tr>
<td></td>
<td>8</td>
<td>1798</td>
<td>81 0.84</td>
<td>0.89</td>
<td></td>
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<tr>
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<td>96 1.05</td>
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<td>10</td>
<td>2565</td>
<td>131 1.31</td>
<td>1.47</td>
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<tr>
<td></td>
<td>11</td>
<td>2215</td>
<td>102 1.03</td>
<td>0.99</td>
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<tr>
<td></td>
<td>12</td>
<td>2412</td>
<td>107 1.05</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>2371</td>
<td>130 0.99</td>
<td>1.15</td>
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<tr>
<td></td>
<td>14</td>
<td>1763</td>
<td>115 0.76</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1428</td>
<td>86 0.65</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1499</td>
<td>142 0.81</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>1741</td>
<td>151 1.11</td>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>2158</td>
<td>174 1.39</td>
<td>1.38</td>
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<td>19</td>
<td>1353</td>
<td>87 0.75</td>
<td>0.56</td>
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<tr>
<td></td>
<td>20</td>
<td>1445</td>
<td>128 0.83</td>
<td>0.93</td>
<td></td>
</tr>
</tbody>
</table>

NC = not counted as all subjects were not enrolled yet.
- = the first three weeks in which averages were determined
1:3 represents the acute:chronic work ratio where 1 = current week pitch count or soreness sum for the week and 3 represent the average pitch count or soreness for the previous 3 weeks of athletic participation.
pitch volume was instituted to limit recall bias and was most feasible for this study. These methods are similar to previous youth baseball research that recorded pitching logs except that in this study both practice and game pitch volume was recorded. This is more consistent with obtaining continuous workload as has been recommended. Counting each pitch is more accurate, however, in a collegiate baseball setting, it was not feasible for the athletic trainer to count every single throw for all of the pitchers. Self-reporting pitch volume and arm soreness allowed the researchers to track daily workload and perceived soreness without undue burden on the athlete. Based on the results these seem to be reasonably useful and straightforward indicators of workload on the pitcher that are moderately correlated both for the entire season and over weekly intervals. Ultimately, the goal of future studies would be to use this information to predict and prevent injuries.

Spikes in both external and internal acute workloads have increased the risk of injury. Acute spikes in external workload creating a negative training balance indicated by an acute to chronic workload was found to increase the relative risk of injury in the subsequent week (RR = 2.1 CI 1.8 to 2.4). Similarly, acute spikes in internal workloads creating a negative training balance increases the relative risk of injury in subsequent week (RR = 2.2 CI 1.91 to 2.5). These results in cricket bowlers suggest that either internal or external workloads could be beneficial to track for injury risk.

The recent consensus statement on monitoring athletic workloads has suggested that integrating both of these measures would be a better representation of total workload. However, in the current study only external workload was measured. Total workload integrating internal with the external workload of pitch volume may have yielded a stronger correlation to arm soreness. It is apparent that a negative training stress measured from either internal or external workload over the previous training weeks, increased the relative risk of injury by two fold as 63% percent of the cricket bowlers' injuries occurred one week after a negative training balance.

Negative training stress was observed in two of the seven pitchers that led to a time-loss injury within two weeks after returning to practice. Although not the focus of this study, it was noted that two individual athletes acute to chronic workload had a negative training stress that led to a time-loss injury. A reliever in the fall was averaging 65 throws a week for six weeks and then developed bronchitis, which reduced his throws to 54 and 45 for the next two weeks, respectively. In the subsequent two weeks, he threw an average of 71 pitches, which is a 1.25 acute to chronic workload change. This indicates that he increased his volume by 25% in both weeks over the previous three weeks. Midway through the second week, he reported elbow pain and was not able to participate in the last few weeks of fall ball due to elbow pain. A similar scenario occurred in the spring to a starting pitcher that developed mononucleous in the 13th week of the 20-week spring season. After two weeks of no throwing in week 15 he participated in partial practice and threw 115 throws. Week 16 his volume increased to 401 throws resulting in a chronic workload of 39 throws over the previous three weeks. The dramatic increase in throwing volume was precipitated due to playoffs approaching. However, this represented a 10 fold increase in throwing volume (401/39 = 10.3) in one week due to the two weeks of negative training stress caused by his illness. In week 18 he reported shoulder pain to the medical staff, resulting in missing two full days and was limited on a third day. This is the first study to analyze acute to chronic external workloads in collegiate baseball players. In cricket, fast bowlers who have a high acute workload have an increased injury incidence over the next three weeks. These examples support the need to monitor pitch volume throughout the season. Monitoring pitch count during a game only represents 12% of the total throws during a collegiate season.

Pitch counts during a game may not be an adequate representation of the workload for college pitchers. Game pitch volume for an entire season depends on if the player is a starter or reliever. Starters have been found to throw 1244 ± 387 and relievers 605 ± 182 pitches. These values are consistent with the 4,593 game pitches recorded in the current study. Averaged over the seven pitchers during the spring season this equals 656 pitches. This is consistent as five of the seven pitchers were relievers. However,
the 4,593 pitches only represents 12% of the total workload for the spring season. Over the course of the season, 45% of all throws were of relatively light intensity classified as “catch”. However, the physical demands from flatground, long toss, and practice bullpens thrown by these seven pitchers which account for 20,283/54,151 (37.4%) pitches thrown are typically not taken into consideration by coaches and medical staff as measuring volume during practice is challenging. Practice pitch volume is four times greater than game pitch volume. It is clear that these practice volumes are critical to prepare the athlete for the demands of pitching while inadequate volume associated with acute spikes can lead to muscle soreness and in some cases time-loss injuries.

This study has several limitations that should be addressed in future research. One limitation of this study is that there is a small sample size. The data recorded was only external workloads of seven Division 1 collegiate baseball pitchers from the Midwest, for one season. Although positive correlations were found, future research should enroll a larger number of participants, incorporating internal with external workload measures and consider other rolling averages to identify the best predictive models for both time-loss and non-time loss injuries should be investigated. Another limitation is that the pitch volume totals are estimations and are not exact pitch counts. The recent advances in wearable technology will likely improve these estimates dramatically and reduce burden on athletes and researchers to monitor number of throws. Other measures of internal workload such as perceived exertion beyond soreness should be considered to identify best predictors of pitchers at risk for injury.

CONCLUSIONS
The primary purpose of this study was to examine the relationship between pitch volume and self-reported arm soreness. There was a moderate and significant correlation (r = .72) over the course of the entire season. As pitch volume and workload increased per week, soreness levels increased as well. This is relevant because current researchers have shown that an increase in workload is associated with injury and daily soreness is considered muscle damage, which can affect muscle function. The secondary purpose was to evaluate the relationship between change in pitch volume and change in arm soreness over the course of the season for collegiate baseball pitchers. Researchers have shown that the greater the workload increases, the larger the increase of risk of injury the following week. In this study, there was a significant and moderate correlation (r = .62) between weekly workload and soreness. Current literature shows that injury risks are not increased immediately after increases in workload, however three to four weeks after the increased acute load relative to previous weeks of training is when injury may occur. The monitoring of acute and chronic workload can offer valuable insight into likelihood of injury.

REFERENCES
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ABSTRACT

Background: The Selective Functional Movement Assessment (SFMA) is a popular assessment tool used to observe and detect components of dysfunctional movement patterns. The goal of the assessment is to identify impairments throughout the kinetic chain that may be contributing to movement dysfunction and/or pain.

Hypothesis/Purpose: The purpose of this research was to determine the intra- and inter-rater reliability of the 10 top-tier movements of the SFMA using the categorical scoring system. It was hypothesized the intra- and inter-rater reliability of the SFMA would be acceptable with variations based on the objectivity of the scoring criteria and the experience of the rater.

Study Design: Cross-sectional reliability study.

Methods: 25 (17 male, 8 female), physically active participants (age: 21.2±1.6 years, height: 177.1±10.7 cm, weight: 74.9±13.9 kg) were independently assessed in real time by three clinicians during two separate visits to the lab using a standard instructional script. Clinicians had varying levels of experience with the SFMA and the two visits occurred a minimum of 48 hours and maximum of seven days apart. Results from each clinician were compared within and between raters using the Kappa coefficient and ratings of absolute agreement.

Results: Overall, slight to substantial intra- and inter-rater reliability were observed using the categorical scoring tool, although variations existed depending on the movement pattern. Kappa coefficients for intra-rater reliability ranged from 0.21-1.00, while % absolute agreement ranged from 0.64-1.00. Inter-rater reliability for the same measures ranged from 0.11-0.89 and 0.52-0.96 respectively. Clinicians certified in the SFMA with the greatest amount of experience using the SFMA demonstrated higher intra-rater reliability. Similarly, higher inter-rater reliability was found between certified raters with the most experience.

Conclusions: Certified SFMA raters with greater amounts of experience can demonstrate adequate intra- and inter-rater reliability using the categorical scoring method.

Level of Evidence: 2, Reliability study

Keywords: Dysfunction, functional movement, movement screen, movement system, repeatability

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The authors do not have any conflicts of interest to disclose regarding the research.
INTRODUCTION
The Selective Functional Movement Assessment (SFMA) is one of the many tools used by health care professionals to observe movement restrictions in individuals with known musculoskeletal injuries. While the reliability of the Functional Movement Screen™ (FMS™) has been heavily studied, only two published studies have examined the SFMA.1,2 The SFMA consists of ten functional movement patterns involving both the upper and lower extremities and is scored by a trained clinician based on the quality of movement.3 Using this assessment, the clinician can identify dysfunctional and/or painful movement patterns and detect components of the patterns to determine the possible causes. This differentiates the SFMA as an assessment tool used for evaluating injured subjects as opposed to the FMS™ which is designed to screen healthy participants. Ultimately, when using the movement assessment, the clinician is able to identify if the dysfunctional movement is caused by tissue extensibility, joint mobility, or stability/motor control dysfunction.3,4 At the core of the assessment is the concept of regional interdependence.5 This notion allows the clinician to identify impairments within the kinetic chain that may seem unrelated to the primary complaint, but may contribute to their movement dysfunction.3

Similar to the FMS™, the SFMA must be determined to be reliable prior to investigating other factors such as corrective exercises or specific treatment interventions. Multiple investigations have examined the reliability of the FMS™ under a variety of contexts and two recent systematic reviews found the screen to be a reliable method for evaluating motion.6,7 However, unlike the FMS™, the SFMA is designed to be used in the presence of pain as part of a comprehensive musculoskeletal evaluation. It is paramount that clinicians can trust that the results of their SFMA exam are reliable when making decisions regarding patient status, progression, and discharge.

Previous SFMA reliability studies examined healthy participants using video analysis1 or unhealthy participants using both video analysis and real-time scoring.2 Prior to implementing the assessment as part of a clinician’s practice, it is necessary to establish the real-time reliability of the assessment on a healthy population since the individual’s pain and/or dysfunction could alter movement patterns between sessions and affect scoring. Furthermore, the SFMA was designed to be scored real-time and many clinicians do not have the time to review videos of their patients. Therefore, the primary purpose of this study was to examine the inter- and intra-rater reliability of the 10 top-tier SFMA tests using real-time scoring among raters of different education and experience levels with the assessment in a healthy population. The authors hypothesized that movements with objective benchmarks would be scored more reliably than movements that contained subjective criteria. Furthermore, the authors hypothesized that raters with more experience would exhibit higher intra-rater reliability scores.

METHODS
Participants
A convenience sample of 25 (17 male, 8 female) physically active, college-aged participants volunteered to participate in the study. The average age, height, and mass of the participants were 21.2±1.6 years, 177.1±10.7 cm, and 74.9±13.9 kg respectively. All participants were asked to complete a basic pre-participation questionnaire, which included age, sex, height, weight, previous musculoskeletal injuries, and activity level per week. To be included, participants needed to be physically active for ≥30 min on three or more days per week. Participants were excluded if they were currently suffering from any musculoskeletal injury that affected their physical activity participation, had undergone any surgery within the prior six months, self-reported any neurologic conditions, or were pregnant. Before the second testing session, examiners reviewed participant’s health history information to ensure no changes had occurred. A healthy population was recruited for the study in an attempt to establish the reliability of the assessment without the potential influence of pain and/or dysfunction. Prior to beginning data collection, the study was reviewed and approved by the university’s institutional review board. All participants provided written informed consent prior to study participation.

Instrumentation
Participants were scored in real time using the 10 top-tier patterns of the SFMA during two visits to the
lab, each separated by a minimum of 48 hours and maximum of seven days. The SFMA is comprised of the following fundamental movement patterns: 1) Cervical flexion, 2) Cervical extension, 3) Cervical rotation, 4) Upper extremity pattern 1 (medial rotation, adduction, extension), 5) Upper extremity pattern 2 (lateral rotation, abduction, flexion), 6) Multi-segmental flexion, 7) Multi-segmental extension, 8) Multi-segmental rotation, 9) Single leg balance, 10) Overhead deep squat. Each movement was scored categorically based on function and pain into one of four categories (Functional non-painful-FN, Functional painful-FP, Dysfunctional non-painful-DN, or Dysfunctional painful-DP). Participants were not familiar with or taught the grading criteria for any of the movements. A standard verbal script was read to each participant for the desired movement by the same rater (Appendix A). Participants were instructed to alert the raters of any pain experienced during the 10 movements. The movement instructions and scoring criteria were based on those presented in the SFMA Level 1 course4 and detailed in previous publications.1,3

Raters included one athletic training faculty member with 15 hours of SFMA training, SFMA Level 1 certification, and two years’ experience scoring the SFMA (Rater A), one physical therapist with 15 hours of SFMA training, SFMA Level 1 certification, and one year of experience with SFMA (Rater B), and one athletic training student without SFMA certification and no formal training (Rater C). The undergraduate athletic training student had no formal training with the SFMA, however, he did complete a summer internship and worked closely with a physical therapist that used the SFMA on a daily basis. All raters were provided up-to-date, detailed instructions on the SFMA scoring prior to the study. All three raters were present during the data collection sessions and were allowed to move freely about to evaluate each participant’s movement. If needed, raters were allowed to ask the participant to repeat the movement pattern and all raters were allowed an opportunity to re-score the movement. Raters did not confer prior to evaluating the movement and each rater was blinded to the scoring of the other raters. Furthermore, the raters used new scoring sheets for each participant, therefore, the raters were unaware of how they scored the movement during the participant’s first visit.

Procedures
Participants arrived to the lab and the informed consent was obtained from each participant prior to testing. Following completion of the informed consent, participants completed a pre-participation questionnaire that included demographic information and evaluated the participant for the inclusion/exclusion criteria. The standard instructional script was read to each participant for all movements during both visits. The primary investigator (Rater A) also provided a visual demonstration of each movement prior to the participants’ attempt. If necessary, the script was repeated and each of the raters visually verified the movements for correct execution. Movements were scored in the order presented by the SFMA manual,4 beginning with the cervical flexion test and ending with the overhead deep squat. All three raters performed their ratings upon completion of the subject. Evaluators did not cue the participant during any of the movements, nor did they discuss how they scored the movements at any time during or after data collection.

Statistical Analyses
All raw data were initially entered into Microsoft Excel 2016 (Microsoft, Redmond, VA). Data were reduced and copied to SPSS (version 21; IBM Corporation, Armonk, NY) for statistical analysis. Because the goal of the study was to establish the reliability of the individual movement pattern, the authors were not concerned about the movement direction or limb (right/left). Therefore, movements that had a right/left component were pooled together for analysis (i.e. left and right cervical rotation pooled together as cervical rotation). Categorical scores were compared within and between raters (A-B, A-C, and B-C) using both absolute agreement and the Kappa coefficient. The 95% confidence interval (CI) for the Kappa coefficient was calculated using the formula recommended by McHugh8 (κ - 1.96 x SEκ to κ + 1.96 x SEκ). The strength of agreement was assessed using the Kappa coefficient and the interpretation has been previously described as ≤0.1 = poor, 0.1-0.2 = slight, 0.21-0.4 = fair, 0.41-0.6 = moderate, and 0.61-0.8 = substantial, and 0.81-1.0 = almost perfect.9
RESULTS
All 25 participants completed both testing sessions and their data were used for analysis. None of the participants experienced pain during any of the movements. As a group, participants were scored FN most frequently on the cervical flexion pattern (79%) followed by the upper extremity pattern 2 (lateral rotation and flexion; 77%). Participants scored DN most frequently on the single leg stance (77%) followed by the overhead deep squat (75%) and upper extremity pattern 1 (medial rotation and extension; 73%). Rater B scored the highest number of dysfunctional movements followed by Rater A and C respectively.

Results for intra-rater reliability (Kappa, 95% CI, and % agreement) for each rater are presented in Table 1. Kappa values for all raters ranged from slight to substantial depending on the movement pattern evaluated. Rater A demonstrated the highest intra-rater reliability followed by B, and C respectively. The highest intra-rater reliability for all raters occurred during the overhead deep squat followed by the cervical flexion test. The lowest intra-rater reliability for all raters occurred during the cervical extension test (Figure 1), followed by single-leg stance (Figure 2) and multisegmental extension test (Figure 3). Results for the inter-rater reliability (Kappa, 95% CI, and % agreement) are presented in Table 2. Kappa values for all raters ranged from slight to substantial depending on the movement pattern evaluated. Highest inter-rater reliability occurred between raters A & B, followed by A & C, and B & C respectively. The cervical flexion test showed the highest inter-rater reliability while multisegmental extension (Figure 3) showed the lowest inter-rater reliability, followed by cervical rotation (Figure 4).

Table 1. Intra-rater reliability of the categorical scoring of the SFMA presented as Kappa coefficient (95% CIs) and agreement (%).

<table>
<thead>
<tr>
<th>Rater</th>
<th>C Flex</th>
<th>C Ext</th>
<th>C Rot</th>
<th>MRE</th>
<th>LRF</th>
<th>MSF</th>
<th>MSE</th>
<th>MSR</th>
<th>SLS</th>
<th>ODS</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.64 (0.34-0.94)</td>
<td>0.68 (0.30-0.92)</td>
<td>0.68 (0.37-0.82)</td>
<td>0.57 (0.29-0.79)</td>
<td>0.70 (0.23-0.89)</td>
<td>0.75 (0.50-0.96)</td>
<td>0.80 (0.60-0.89)</td>
<td>0.70 (0.40-0.88)</td>
<td>0.80 (0.60-0.88)</td>
<td>0.80 (0.60-0.88)</td>
<td>0.55 (0.20-0.82)</td>
<td>0.17</td>
</tr>
<tr>
<td>B</td>
<td>0.57 (0.31-0.83)</td>
<td>0.69 (0.35-0.84)</td>
<td>0.70 (0.35-0.84)</td>
<td>0.64 (0.32-0.84)</td>
<td>0.78 (0.28-0.86)</td>
<td>0.70 (0.50-0.89)</td>
<td>0.78 (0.40-0.88)</td>
<td>0.76 (0.40-0.88)</td>
<td>0.80 (0.60-0.88)</td>
<td>0.80 (0.60-0.88)</td>
<td>0.50 (0.20-0.82)</td>
<td>0.09</td>
</tr>
<tr>
<td>C</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.84 (0.62-0.96)</td>
<td>0.78 (0.40-0.88)</td>
<td>0.10</td>
</tr>
</tbody>
</table>

CI= confidence interval; C Flex= cervical flexion; C Ext= cervical extension; C Rot= cervical rotation; MRE= mediolateral rotation; LRF= lateral rotation flexion; MSF= multisegmental flexion; MRE= mediolateral rotation; LRF= lateral rotation flexion; MSF= multisegmental flexion; MRE= mediolateral rotation; LRF= lateral rotation flexion; MSF= multisegmental flexion; ODS= overhead deep squat; SD= standard deviation
The purpose of this study was to examine the reliability of scoring the 10 top-tier SFMA tests using real time scoring in a group of healthy participants. The goal was to blend methodology from the two previous SFMA reliability studies in order to examine the repeatability of the assessment. Overall, the results showed slight to substantial reliability and this compared similarly to previously published SFMA reliability studies. Because the previous SFMA reliability study on a healthy population used video analysis, this study aimed to reproduce these results.

### DISCUSSION

The purpose of this study was to examine the reliability of scoring the 10 top-tier SFMA tests using real time scoring in a group of healthy participants. The goal was to blend methodology from the two previous SFMA reliability studies in order to examine the repeatability of the assessment. Overall, the results showed slight to substantial reliability and this compared similarly to previously published SFMA reliability studies. Because the previous SFMA reliability study on a healthy population used video analysis, this study aimed to reproduce these results.

### Table 2. Inter-rater reliability of the categorical scoring of the SFMA presented as Kappa coefficient (95% CIs) and agreement (%).

<table>
<thead>
<tr>
<th>Test</th>
<th>Rater A-B</th>
<th>Rater A-C</th>
<th>Rater B-C</th>
<th>Mean of All Raters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kappa</td>
<td>Agree</td>
<td>Kappa</td>
<td>Agree</td>
</tr>
<tr>
<td>C Flex</td>
<td>0.89 (0.69-1.09)</td>
<td>0.96</td>
<td>0.89 (0.69-1.09)</td>
<td>0.96</td>
</tr>
<tr>
<td>C Ext</td>
<td>0.69 (0.42-0.96)</td>
<td>0.84</td>
<td>0.36 (0.01-0.71)</td>
<td>0.72</td>
</tr>
<tr>
<td>C Rot</td>
<td>0.44 (0.22-0.67)</td>
<td>0.76</td>
<td>0.24 (0.08-0.40)</td>
<td>0.58</td>
</tr>
<tr>
<td>MRE</td>
<td>0.55 (0.30-0.80)</td>
<td>0.84</td>
<td>0.43 (0.13-0.73)</td>
<td>0.82</td>
</tr>
<tr>
<td>LRF</td>
<td>0.55 (0.29-0.80)</td>
<td>0.84</td>
<td>0.51 (0.20-0.82)</td>
<td>0.86</td>
</tr>
<tr>
<td>MSF</td>
<td>0.66 (0.37-0.95)</td>
<td>0.84</td>
<td>0.60 (0.25-0.95)</td>
<td>0.84</td>
</tr>
<tr>
<td>MSE</td>
<td>0.21 (0.01-0.41)</td>
<td>0.52</td>
<td>0.14 (-0.18-0.46)</td>
<td>0.56</td>
</tr>
<tr>
<td>MSR</td>
<td>0.50 (0.29-0.71)</td>
<td>0.74</td>
<td>0.43 (0.18-0.68)</td>
<td>0.72</td>
</tr>
<tr>
<td>SLS</td>
<td>0.27 (-0.15-0.69)</td>
<td>0.72</td>
<td>0.36 (-0.02-0.74)</td>
<td>0.72</td>
</tr>
<tr>
<td>ODS</td>
<td>0.69 (0.35-1.00)</td>
<td>0.88</td>
<td>0.72 (0.46-0.98)</td>
<td>0.88</td>
</tr>
</tbody>
</table>

CI= confidence interval; C Flex= cervical flexion; C Ext= cervical extension; C Rot= cervical rotation; MRE= medial rotation extension; LRF= lateral rotation flexion; MSF= multisegmental flexion; MSE= multisegmental extension; MSR= multisegmental rotation; SLS= single leg stance; ODS= overhead deep squat; SD= standard deviation
methods but score all participants real-time to simulate how the assessment is typically used in clinical practice. Conversely, the only other SFMA reliability study examined a clinical population with a known pathology. While this replicates the intended purpose of the assessment, pain and/or dysfunction has the potential to affect the reliability. In theory, movements are more likely to be repeatable in an otherwise healthy population because there is less likelihood of pain affecting the movement pattern.

Both the FMS™ and the SFMA are movement systems that allow the clinician to evaluate movement quality. Cook suggests that clinicians are knowledgeable in both techniques to understand how the two systems can complement one another. The SFMA is designed to be a systematic method for observing movement pattern dysfunction in a pathologic population to determine the root cause of the pain and/or dysfunction. These results can then guide potential clinical interventions. Conversely, the FMS™ is designed to be utilized with healthy participants in an attempt to guide programming decisions and provide movement feedback. Despite these differences, the two systems still share many similarities in their approach to assessing movement and two of the movement patterns are nearly identical.

A search for articles involving the SFMA revealed less than five peer-reviewed journal articles. As previously mentioned, several differences in methodology existed between the current study and the two published articles. First, both previously published studies used video recording for scoring participants. All three raters used video recordings to score participants in the Glaws et al. study, while Dolbeer et al. had two raters score real time and one score using video. While this is feasible for conducting research, Dolbeer et al. acknowledged that the SFMA is intended to be scored real time in the clinical setting and not intended for 2-dimensional video analysis. Second, Dolbeer et al. used a clinical physical therapy population, therefore, some of their participants exhibited painful patterns. Both Glaws et al. and the current study used a healthy population and no painful patterns were recorded. Third, both Glaws et al. and the current study examined both intra- and inter-rater reliability while Dolbeer et al. only evaluated inter-rater reliability. In many clinical practices, the same clinician works with the patient and tracks movement progress, making it necessary to establish the intra-rater reliability. However, having the ability to allow another clinician to evaluate movement performance allows the system to become more versatile within a clinical practice with multiple clinicians sharing the patient load. Fourth, both the current study and Glaws et al. used examiners with differing levels of experience with the SFMA while Dolbeer et al. used examiners with similar levels of experience. While data from the current study may have been different if all of the examiners had the same level of experience, it is unlikely clinicians working together would all have the same level of experience. Finally, both previously published studies used both categorical and the criterion checklist scoring tool that is included in the SFMA manual to assess reliability. The current study only evaluated the reliability of the categorical scoring method. Additionally, the authors chose to only examine the categorical scoring method since these results determine if it is necessary to perform the breakouts associated with each of the movement patterns.

Figure 4. Cervical rotation test.
Despite these differences, the results demonstrated slightly lower intra-rater reliability and slightly higher inter-rater reliability when compared with Glaws et al.\textsuperscript{1} Furthermore, the results demonstrated similar to slightly higher inter-rater reliability depending on which set of examiners were being compared. The current study found similar to slightly higher inter-rater reliability when comparing the Dolbeer et al.\textsuperscript{2} study. However, some of this variation could be attributed to the presence of dysfunctional and/or painful movement patterns in the patients' evaluated in both studies. Based on how the Cohen's Kappa statistic is calculated, the Kappa coefficient can be lowered with small samples of a given categorical score.\textsuperscript{10} Because the distribution of FN, DN, FP, and DP scores for some movement patterns were not evenly distributed for various movement patterns, the overall interpretation of the Kappa statistic may have been lowered. The purpose of the Kappa statistic is to take into account the possibility that raters guessed on scores.\textsuperscript{8} With unequal distributions of scores, the Kappa statistic may have the potential to be excessively lowered.\textsuperscript{8} This may explain why there were large differences in the Kappa statistic and the absolute agreement for some of the movement patterns.

**Intra-Rater Reliability**
The intra-rater reliability Kappa coefficients for all raters in theGlaws et al.\textsuperscript{1} study ranged from 0.25 to 0.94 for the 10 fundamental movements. The most reliable rater in the Glaws et al.\textsuperscript{1} study had Kappa coefficient values ranging from 0.41 to 0.94. The results from the current study demonstrated intra-rater reliability Kappa coefficients for all raters ranging from 0.21 to 1.00. The most reliable rater from the current study demonstrated Kappa coefficients ranging from 0.38 to 0.90. Values for absolute agreement from the Glaws et al.\textsuperscript{1} study ranged from 0.63 to 0.97 while the results from the current study ranged from 0.64 to 1.00. While these ranges are strikingly similar, examining the individual movements revealed some substantial differences. For example, by averaging the results for all raters, cervical extension demonstrated the lowest intra-rater reliability (0.30) in the current study while this was the most reliability movement (0.77) in the Glaws et al.\textsuperscript{1} study. Alternatively, multisegmental extension was among the least reliable movements in both studies with Kappa coefficients ranging from 0.36 to 0.49. Similarly, cervical rotation demonstrated lower reliability values while multisegmental flexion revealed higher reliability values. While the overall reliability results were similar when averaging all movement patterns, the two studies found discrepancies in the reliability for certain movement patterns.

**Inter-Rater Reliability**
Results from the current study showed inter-rater reliability Kappa coefficient values ranging from 0.11 to 0.89 for all raters. Glaws et al. reported values ranging from 0.07 to 0.97 for all raters while Dolbeer et al. reported values ranging from 0.1 to 0.96. Raters A and B displayed the highest reliability while raters B & C were the lowest. These data were similar to the Glaws et al.\textsuperscript{1} study which also found level of experience was reflective of the inter-rater reliability. For all sets of raters in the current study, multisegmental extension exhibited the lowest inter-rater reliability, while cervical flexion demonstrated the highest. These same results were not found in the two previously published reliability studies.\textsuperscript{1,2} Inter-rater reliability between sets of examiners revealed inconsistent results for the highest and lowest reliability values.

**Top-Tier SFMA Movements**
Regardless of the movement pattern being evaluated, clinicians must evaluate the pattern for excessive effort and/or lack of motor control. While this tends to be a subjective component of the evaluation, with practice, clinicians are better able to pick up on the cues associated with both excessive effort and lack of motor control. The current results demonstrated the lowest reliability numbers for cervical extension, cervical rotation, and MSE. Of these movements, the cervical rotation movement contains the most objective criteria by providing the midpoint of the clavicle as the target anatomical landmark. To be considered FN, the participant must rotate only the cervical spine so that the chin is aligned with the midpoint of the clavicle. While this movement contains objective criteria, it does require the examiner to reliably assess the mid-point of the clavicle. In contrast, both the cervical and multisegmental extension patterns require the examiner to assess
the participant for a ‘uniform’ spinal curve during the movement. While this is only one component of the evaluation criteria, the subjective nature of assessing a uniform spinal curve likely contributed to lower reliability scores for these movements.

The movements with the highest reliability tended to have the most objective scoring criteria. For example, in order to be considered FN for the cervical flexion pattern, the participant must flex the neck and touch the chin to the chest. Similarly, the multisegmental flexion test contains several objective criteria such as touching the fingers to the ground, a posterior weight shift, and a sacral angle of greater than 70°. Interestingly, the multisegmental flexion test also requires the participant to have a uniform spine curve, however, the reliability of assessing this motion was considerably higher than the multisegmental extension movement. A possible explanation for this could be the difficulty in visualizing the lumbar spine extension due to the reduction of this space during extension. Furthermore, not being able to touch the toes during the multisegmental flexion test immediately places it in the dysfunctional category. It is possible the reliability of the multisegmental flexion test is higher because the rater knowingly or unknowingly places more emphasis on evaluating the objective portions of the test and less on the subjective portions.

LIMITATIONS
As with all research investigations, this study was not without limitations. All participants were healthy at the time of testing; therefore, no painful patterns were identified. The SFMA is designed to identify dysfunctional movement patterns in participants with known musculoskeletal injury. Secondly, the authors chose to assess only the intra- and inter-rater reliability of the categorical scoring system of the SFMA. The system allows clinicians to score participants based on both a categorical and criterion checklist system. The authors also chose to evaluate only the reliability of the categorical system because this system dictates what movements receive further attention. Third, movements were scored real-time by all participants. This reflects the intended design of the assessment; however, it does not allow evaluators to watch the movement multiple times. However, all evaluators had the ability to ask the participant to perform the movement again, which allowed the evaluator to take a second look or evaluate the movement from a different angle. It is possible the individual only narrowly passed/failed the movement during the first session or attempt and the opposite interpretation was found during the second visit or attempt. Naturally, this would negatively affect the reliability but does reflect the same challenges a clinician would find in clinical practice. Fourth, the current study utilized a sample of healthy, college-aged participants which may make it difficult to generalize the findings to other populations. Finally, examiners differed in their experience level with the assessment. While it may be helpful to know the reliability of a homogenous set of examiners, many clinical settings where the SFMA is performed contain a variety of clinicians with varying levels of SFMA experience.

CONCLUSIONS
The top-tier movements of the SFMA scored categorically and assessed real-time in a healthy population demonstrated slight to substantial reliability. The methodology of this study combines aspects of previous SFMA reliability studies and further supports their findings. Both intra- and inter-rater reliability was highest for raters that had the most experience and were certified in the SFMA. It appears movements with the most objective scoring criteria produce the highest reliability values.

REFERENCES


The starting position for all tests is the same. You will stand erect with your feet together, toes pointing forward, and your arms hanging comfortably by your side. We will read you the instructions and then ask you to perform the movement so we can score the quality and quantity via visual inspection. If you experience pain anywhere in your body during the movement, please let the examiner know.

1. **Cervical Spine Flexion**: Please attempt to touch your chin to your breastbone (sternum) while keeping your trunk erect during the movement.

2. **Cervical Spine Extension**: Please extend your head back like you are looking at the ceiling as far as possible while keeping your trunk erect during the movement.

3. **Cervical Spine Rotation**: Please rotate only your head as far as possible to the right. Repeat this movement to the left.

4. **Upper Extremity Pattern 1**: Please reach back with your right arm and try to touch where I have placed my finger on your left inferior scapula. Repeat this movement with your left arm, touching the spot I have marked.

5. **Upper Extremity Pattern 2**: Please reach overhead with your right arm and try to touch where I have placed my finger on your left scapular spine.

6. **Multi-Segmental Flexion**: Please bend forward at the hips while reaching your hands toward your toes. Try to touch the tips of your fingers to the end of the toes without bending your knees.

7. **Multi-Segmental Extension**: Please raise your hands above your head with your arms fully extended and the elbows in-line with the ears. Bend backward as far as possible, making sure your hips go forward and arms go back simultaneously.

8. **Multi-Segmental Rotation**: Please rotate the entire body (hips, shoulders, and head), as far as possible to the right while the feet position remains unchanged. Repeat this movement but rotate to the left.

9. **Single Leg Stance**: Lift your right leg so the hip and knee are both at 90-degree angles. Remain in this posture for 10 seconds. Rest for as long as you need and then repeat this task with your eyes closed. Repeat both tests with lifting your left leg.

10. **Overhead Deep Squat**: Please stand with the instep of your feet in vertical alignment with the outside of the shoulders. Your feet should be pointing straight forward. Extend your hands overhead with the shoulders flexed and abducted and the elbows fully extended (this will be demonstrated). Slowly descend as deeply as possible into a squat position. Maintain the heels in contact with the floor, your head and chest should remain facing forward, and the arms maximally pressed overhead. Return to the starting position.
ABSTRACT

Background: Interventions exercises have been developed to help athletes improve scores on the Functional Movement Screen™ (FMS™). However, there is a paucity of research on the effects of a similar program in female athletes, as well as the effects of a standardized corrective exercise regimen. The purpose of this study was to assess whether an in-season, standardized interventional exercise program improves FMS™ score asymmetry and the composite score of female collegiate athletes.

Study Design: Prospective, quasi-experimental, cohort study

Methods: Forty-one (mean age 19.5 ± 1.2 years; body mass, 70.6 ± 11.5 kg; height, 1.70 ± 0.083 m) NCAA Division III female soccer (n=10), softball (n=17), and basketball (n=14) players participated in this study. The athletes completed the FMS™ screens prior to their season, regularly participated in four in-season standardized corrective exercises throughout three to four month athletic seasons, and completed the FMS™ screens in the postseason.

Results: The average score of all athletes before the season was 15.52 ± 0.63 and 16.04 ± 0.72 after the season. While the mean score of soccer players increased from 14.80 ± 0.92 to 16.1 ± 1.52 and the mean score of softball players increased from 15.83 ± 1.89 to 16.72 ± 1.41 at the end of the season, the mean score of basketball players dropped from 15.93 ± 1.49 to 15.29 ± 1.59. Women’s basketball players experienced a decrease in their composite FMS™ score (¯x = -0.571, p<0.01), while women’s soccer players (¯x = +1.30, p<0.05) and softball players (¯x = +1.12, p<0.05) experienced an increase in mean score 2.28 times and 1.96 times greater in magnitude than the decrease in basketball players' composite FMS™, respectively. Fewer total athletes demonstrated asymmetries at postseason testing, decreasing from 24 at preseason testing to 15 at postseason testing (p<0.01). Significant differences were not noted between athlete age and FMS™ scores (p>0.05).

Conclusions: Standardized interventional programs during athletic teams' seasons may be used to help increase FMS™ scores and reduce asymmetry. Though more studies are warranted to address the negative effects of this standardized program in women’s basketball players, this study demonstrated that the number of asymmetries significantly decreased from pre- to postseason among soccer and softball players, which may have implications for a higher resistance to injury.

Levels of Evidence: 3

Keywords: Asymmetry, corrective exercises, female athletes, Functional Movement Screen™ (FMS™), Movement system
INTRODUCTION
Musculoskeletal injury in the athletic population can be devastating at the individual, team, and organizational levels. Often performance of the team and athlete suffers as a result – which can have both social-emotional and financial consequences dependent on the setting. The involvement of neuromuscular impairment in the pathophysiology of sports injuries prompts interdisciplinary practitioners, including athletic trainers, physical therapists, and physicians, to use screening tools that quantify athletes’ abilities to execute functional movements and hopefully reduce injury risk through primary prevention.\(^1\) The Functional Movement Screen™ (FMS™) is a valid and reliable clinical test that evaluates neuromuscular impairments developed by Functional Movement Systems and Gray Cook.\(^2\) It is comprised of seven functional movements and three clearing tests, and has been used to provide a quantitative measurement of musculoskeletal injury risk.\(^3\)\(^-\)\(^7\) Of clinical importance is the ability to effectively identify movement impairments, and potentially decrease the potential for injury, prevent re-injury, enhance performance and ultimately improve quality of life.\(^4\)

A series of work by Kiesel et al. indicate that performance on the FMS™ has implications for risk of injury in a population of professional football players.\(^7\)\(^-\)\(^9\) One particular trend shown to correlate with a higher incidence of injury was asymmetry in FMS™ scores for movements that assess the extremities. Asymmetry in this context describes differing performance of each extremity (left versus right) when executing a given functional movement, and musculoskeletal asymmetry is a prominent risk factor for injury.\(^10\)\(^-\)\(^14\) Players who scored <14 exhibited at the start of training camp demonstrated a relative risk of 1.87 for time loss injuries over the course of the season. Similarly, players with at least one asymmetry displayed a relative risk of 1.80. The combination of both a low score and exhibiting a movement asymmetry was highly specific (.87) for injury in this athletic population.\(^7\)

Given the use of the FMS™ to gauge injury risk in athletes, it is possible that improvements in FMS™ score and decreased asymmetry correlate with decreased incidence of time loss injuries. Intervventional exercises have been developed to help athletes improve dysfunctional movement patterns, aimed at establishing symmetry and reaching a balance between mobility and stability.\(^8\)\(^-\)\(^15\) Kiesel et al. utilized off-season interventions with corrective exercises that led to improvements in FMS™ scores for male football players, and Bodden et al. demonstrated that FMS™ scores improved in male MMA fighters after an eight-week interventional program. The work of Bodden et al. also indicated that interventional programs hold potential to establish symmetry in functional movements.\(^15\)

However, there is little research on the effects of a similar program on the FMS™ scores of female athletes. While studies have shown no significant differences in the composite FMS™ scores of male and female athletes over the course of an athletic season,\(^1\) similar studies are needed with an intervention in place in order to assess the ability of exercises to change composite FMS™ scores. Furthermore, the corrective exercises instituted by Kiesel et al. and Bodden et al. were unique to each athlete or unique for athletes of a particular sport, which does not address the potential effect of a standardized corrective exercise regimen followed uniformly by athletes across different sports.\(^8\)\(^-\)\(^15\) Although tailoring exercises to a specific sport or individual athletes is a goal of most practitioners, standardization of exercise offers intervention for a greater number of athletes with less dedication of staffing and time resources, which may be a limiting factor for sports medicine programs.

Consequently, the purpose of this study was to assess whether an in-season, standardized interventional exercise program improves FMS™ score asymmetry and the composite score of female collegiate athletes. The authors hypothesized that a standardized interventional program aimed at improving athletes’ functional movements should precipitate improved FMS™ composite scores and reduce asymmetry upon completion of the exercise regimen.

METHODS
Experimental Approach to the Problem
A prospective, quasi-experimental cohort study design was used to analyze changes in the FMS™ after three to four months of in-season interventional
exercises, training, and competitive games in National Collegiate Athletic Association (NCAA) Division III female soccer, softball, and basketball athletes. The athletes completed preseason FMS™ tests before the start of their season as part of their regular preseason evaluation, participated in four standardized corrective exercises as part of routine warm-ups/strength and conditioning programs, and completed postseason FMS™ tests at the end of their respective seasons. Corrective exercises were not conducted during off-season activities. Accordingly, follow up time is measured from the start of each season, and onset of exercise participation, until postseason testing. Athlete recruitment took place in August of 2016, followed by subsequent preseason FMS™ testing. Athletic seasons took place between August 2016 and May 2017 for about three to four months per season, which varied per specific sport. Postseason FMS™ tests were conducted during the last week of each team’s respective competitive season.

Subjects
Forty-one (mean age 19.5 ± 1.2 years; body mass, 70.6 ± 11.5 kg; height, 1.70 ± 0.083 m) NCAA Division III female soccer (n=10), softball (n=17), and basketball (n=14) players participated in this study. This study size reflects female athletes who completed both the preseason and postseason screens, after executing the interventional exercises during their respective competitive seasons. During the regular season for each sport, all subjects participated in team practices and games, which involved three to five court practice sessions and weekly games. The softball and basketball players performed the standardized corrective exercises at the start of their strength-training sessions three times per week with the institution’s strength and conditioning staff. Women’s soccer did not participate in strength training sessions, and accordingly performed the standardized exercises during weekly practice sessions three to four times per week. Exercises were demonstrated and observed by trained physical therapists at the start of the season. Consistent completion of the exercise regimen was addressed through verbal communication with teams through the course of the season. Data for the preseason and postseason FMS™ was collected by trained physical therapy staff members as standard preseason and postseason guidelines described by this study. Postseason testing was conducted at team practice sessions to optimize attendance for follow-up testing.

Inclusion criteria for participation in this study included female athletes, ages 18-25, who presented to both preseason testing and postseason testing after participating in the weekly exercises. Exclusion criteria included any injury sustained at the start of the season, which would prevent the athlete from performing the screen, or athletes younger than 18 years of age. The institution’s Institutional Review Board for Research with Human Subjects approved this study. Informed consent was obtained from subjects prior to collection of data.

Functional Movement Screen™
A team of five physical therapists and athletic trainers used the Functional Movement Screen (FMS™) to assess the athletes’ functional movement patterns. The interdisciplinary team members were experienced in FMS™ scoring to ensure proper evaluation of the subjects. The FMS™ evaluates asymmetry and limitations in seven functional movements through tests including the deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability. The seven functional movement tests are scored on a scale of 0-3, contributing to a maximum total score of 21.5,6,7 Cook et al. describe the exact instructions and grading criteria for completing the seven functional movements tests for the FMS™. Each functional movement tests components of strength, stability and flexibility within their respective regions. Observations of movement patterns and compensation strategies can lead the health professional to examine component in isolation. In addition, there are three clearing tests associated with shoulder mobility, trunk stability push-up, and rotary stability to gauge subject pain while executing the functional movement.

Five stations with a scorer, FMS™ test kit, and FMS™ score sheet were set up in a physical therapy studio. The staff scorer at each station instructed the athletes on how to complete the functional movement tested at the station. Due to staffing limitation different scorers were used during the preseason and postseason FMS™, however, previous studies indicate moderate to excellent interrater reliability of FMS™ and
testers discussed grading criteria prior to both pre and post season testing to ensure consistency.²,⁹,¹⁶

After each test was completed at each station, a score from 0-3 was assigned to the subject per FMS™ grading criteria. A score of 0 was given if the subject experienced pain and a score of 1 was given if the subject could not complete the movement or a loss of balance occurred. A score of 2 was assigned if the subject completed the movement without pain, but exhibited a level of compensation to assist in the movement, whereas a score of 3 was given if the subject completed the movement without pain and compensation.²,⁵⁻⁶

The hurdle step, in-line lunge, shoulder mobility, active straight leg raise, and rotary stability tests are scored separately for the right and left sides of the body, allowing for detection of asymmetry in functional movement. For these tests, the lowest score contributes to the total score assigned for the functional movement test. For example, a right leg score of 1 for the active straight leg raise and left leg score of 2 would translate to a total score of 1 for the active straight leg raise in that subject.

In-Season Activity and Exercises
Following preseason testing, subjects competed in regular season games and participated in four standardized interventional exercises as a part of their routine group warm-up. The exercises were taught by trained physical therapists and incorporated into team warm-ups to ensure equal participation of all subjects. The coaches and team captains monitored the interventional exercises for the soccer players. The team captains and strength and conditioning coaches monitored the interventional exercises for the softball and basketball players. The four standard interventional exercises, each aimed at improving a certain functional movement, included the hard roll, negative push-up, plank hamstring curls, and partner leg-raise (Figure 1). These exercises are not those recommended by Cook et al.,¹⁷ rather these are variations targeted at specific impairments that were identified as deficits at the start of the season across the three recruited teams. Consistently across sports rotary stability was the poorest performing section of FMS™ and this guided exercise selection. The soccer team specifically performed these on their practice surface and did not have equipment readily available. In addition, only four exercises were chosen, as opposed to more, to increase coach and team member compliance. Table I demonstrates the protocol for completion of each exercise and corresponding FMS™ movements.

Statistical Methods
All data were collected and organized using Microsoft Excel. Statistical analysis was conducted and plotted via GraphPad Prism 6 (GraphPad Software Inc., La Jolla, CA USA). Mean and standard deviation were calculated for all FMS™ scores (composite and individual movements), age, height, and weight. Due to limited sample sizes and skewed distributions, the Kruskal-Wallis test (nonparametric) was used to determine any significant differences in the outcome variables (i.e. changes in composite FMS™ scores from preseason to postseason) among the tested sports (softball, soccer, and basketball). When a significant difference was discovered among all participants, Dunn's multiple comparison post-hoc testing was utilized to determine any significant differences between the sports (softball versus soccer, softball versus basketball, and soccer versus basketball) and their respective change in composite FMS™ scores.

As described by Sprague et al. in 2014, a 1-way Chi-squared analysis was performed to determine significant changes between preseason and postseason FMS™ and the number of athletes with asymmetries, using the number of asymmetries at preseason as “expected” values in the Chi-squared analysis.¹ Asymmetries were also analyzed by 2x2 contingency tables (preseason or postseason versus frequency of asymmetries or no asymmetries) with Fischer's test for contingency. Similar analyses were used to determine significant changes in the number of athletes with scores ≤ 1 in any individual movement score. Data pertaining to subjects who only attended preseason testing, and not postseason testing, were not included in any analyses.

RESULTS
Fifty-four athletes initially participated in preseason testing. However, only forty-one (mean age 19.5 ± 1.2 years; mass, 70.6 ± 11.5kg; height, 1.70 ± 0.083 m) NCAA Division III female soccer (n = 10), softball (n = 17), and basketball (n = 14) players presented to both preseason
and postseason testing after participation in the in-season exercises, and were included in outcome analyses. A total of thirteen athletes (basketball, n = 6; softball, n = 1; soccer, n = 6) presented to preseason testing only, and were not included in the analyses. The average follow-up time, as measured from the start of each team’s season to postseason testing, was 111 days, or about 3.7 months.

The average score of all athletes before the season was 15.52 ± 0.63 and 16.04 ± 0.72 after the season. While the mean score of soccer players increased from 14.80 ± 0.92 to 16.1 ± 1.52 and the mean score of softball players increased from 15.83 ± 1.89 to 16.72 ± 1.41 at the end of the season, the mean score of basketball players dropped from 15.93 ± 1.49 to 15.29 ± 1.59.

**Table 1.** Standardized interventional exercise regimen with corresponding FMS™ screen used for assessment.

<table>
<thead>
<tr>
<th>Training</th>
<th>Protocol</th>
<th>FMS Screen™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Roll</td>
<td>2 sets, 10 rep.</td>
<td>Rotary Stability</td>
</tr>
<tr>
<td>Negative Push-Up</td>
<td>3 sets, 12 rep.</td>
<td>Trunk Stability</td>
</tr>
<tr>
<td>Plank Hamstring Curls</td>
<td>2 sets, 10 rep.</td>
<td>Rotary Stability</td>
</tr>
<tr>
<td>Partner Leg Raise</td>
<td>2 sets, 10 rep.</td>
<td>Active Straight Leg Raise</td>
</tr>
</tbody>
</table>

**Figure 1.** Standardized interventional exercises performed by each athlete during team practices, 3-4 times per week. Top to bottom: Hard roll, Negative Push-Up, Plank Hamstring Curls, Partner Leg-Raise.
Among all athletes tested, softball and soccer players demonstrated the greatest frequency of an increase in composite FMS™ score (Figure 2). There was a significant difference between all three sports and the change in composite FMS™ score, as women’s basketball players were more likely to experience decreases in their composite FMS™ score ($\bar{x} = -0.571, p < 0.01$) (Figure 3). In contrast, women’s soccer players ($\bar{x} = +1.30, p < 0.05$) experienced a positive change 2.28 times greater in magnitude than the decrease in basketball players’ composite FMS™. Similarly, softball players ($\bar{x} = +1.12, p < 0.05$) experienced a positive change 1.96 times greater in magnitude than the decrease in basketball players’ composite FMS™. Of note, no significant differences regarding changes in composite FMS™ score were noted between softball and soccer players ($p > 0.05$), indicating that the change in composite FMS™ scores between these two groups was similar. Furthermore, no significant differences were noted between sport and individual movement scores ($p > 0.05$).

Fewer total players demonstrated asymmetries at postseason testing ($n_{\text{preseason}} = 24, n_{\text{postseason}} = 15, p < 0.01$), with significant decreases in asymmetries in soccer ($p = 0.01$) and softball ($p < 0.01$) players (Table 2). The decrease in total asymmetry frequency represented 40% ($n = 4$) of soccer players and 29% ($n = 5$) of softball players. Figure 4 depicts results regarding asymmetries analyzed with Fisher’s test for contingency, indicating a significant decrease in the asymmetries noted among softball players ($p = 0.037$). No significant differences were shown in the number of players with scores ≤ 1 between preseason and postseason testing ($p > 0.05$). Furthermore, significant differences were not noted between athlete age and FMS™ scores ($p > 0.05$).

DISCUSSION

Changes in Composite FMS™ Scores
To the authors’ knowledge, there is currently a paucity of evidence regarding the ability to change FMS™.
scores based on a standardized interventional program in female athletes from multiple sports. This study was conducted to determine whether standardized exercises designed to address FMS™ movements precipitate improved FMS™ scores regardless of the participant’s sport. In settings with lack of ongoing interdisciplinary intervention, standardized exercise may provide a clinically efficient way to promote primary prevention.

The hypothesis that the four prescribed, standard exercises could improve athletes’ FMS™ scores universally was not supported by this study. Though the mean score of all athletes increased at postseason, examining team-specific scores argues against a uniform increase in scores. The novel finding of this study was that women's soccer and softball players experienced an increase in composite FMS™ scores with reduced asymmetries after performing the same four standardized warm-up exercises; however, the women's basketball players experienced a small net negative change in composite FMS™ scores with increased asymmetries.

In a cohort of professional football players, on average there was an 11% increase in their FMS™ score as a result of the interventional training program, which is a greater change than what was experienced in this cohort. The preseason average FMS™ scores noted in this study were higher than the average of 14.3 ± 1.77 among female athletes recorded by Chorba et al. Accordingly, the results from this study differ from past studies that have demonstrated the ability of intervention programs to more uniformly increase FMS™ scores within a cohort of athletes. However, those studies contrasted from this current study in two significant ways. Specifically, this study examined a larger cohort of athletes than Bodden et al.’s study, and this cohort featured athletes from three different sports. Moreover, the differing results may represent a manifestation of gender differences, as this cohort featured solely female athletes, compared to the male MMA athletes and professional football players featured in Kiesel et al. and Bodden et al.’s work. In addition to gender differences, this study featured Division III athletes as opposed to more high-performing semiprofessional MMA fighters and professional American football players. Furthermore, the athletes in this study all completed the same four exercises during their warm-up routines regardless of their sport, as opposed to individualized training programs prescribed by Kiesel et al. and Bodden et al. to their subjects. Although individualized, sport-specific training would be preferred, as supported by the aforementioned studies, this study aimed to develop an exercise regimen that could be implemented across sports with fewer healthcare providers in order to improve functional movement scores in this study’s patient population.
Though the improvement in FMS™ scores observed in the women's soccer and softball athletes supports previous findings that FMS™ composite scores may be improved by corrective exercises, this study shows that interventional exercises may be standardized only for certain sports. However, it is important to keep in mind that the negative change in composite FMS™ score of 0.64 points from preseason to postseason in the basketball cohort is less than the minimally clinically important difference (MCID) for the FMS™ composite score of 1.25 points indicated in previous literature.

The discrepancy between the changes observed in basketball players' individual limb FMS™ scores versus that of the other athletes might indicate the need for sport-specific interventional exercises. The increases in composite FMS™ scores of softball and soccer players indicate that the standardized exercises should have helped increase FMS™ scores without a tropism for upper or lower body dominant sports. However, the basketball players' relatively poor response to the standardized exercises suggests that those athletes were subject to different factors affecting their functional movements, compared to softball and soccer players. The basketball players' FMS™ performance did include some “0” scores due to pain and/or inability to complete the movement although there was no time loss injury associated. Limitations and decreased ability to perform the functional movement occurred over the course of the season, which limited functional scoring but did not limit sport performance. Different interventional exercises specific to the deficits in the basketball players' FMS™ performance may allow for reversal of their negative trend in FMS™ performance in future seasons. Additionally, consideration of dosing, technique and other potential interventions may also need to be considered in the future.

Asymmetries
Asymmetries from the hurdle step, in-line lunge, shoulder mobility, active straight leg raise, and rotary stability tests reflect differences in scoring between the right and left side of the body. In this cohort, a significant overall reduction in the number of asymmetries recorded at postseason testing as compared to preseason scores was observed, particularly in softball players (Table 2, Figure 4). Though the overall number of asymmetries was reduced in the combined cohort of athletes, the basketball cohort actually experienced a slight increase in the number of players with asymmetry in scores. This finding represents a distinct deviation from the trend observed in softball and soccer players. Though the observed increased asymmetry in basketball players may represent a true finding, it is possible that this phenomenon may be due to errors in instruction from the basketball team staff. Specifically, improper technique may have favored one side of the body over the other, causing an augmentation of asymmetry that compounded with asymmetry introduced by playing basketball through the season (i.e. inherent left or right handed preference for dribbling, shooting, or passing). In contrast, the reduction in the number of asymmetries in the women's soccer and softball players' scores from preseason to postseason suggests potential of using these standardized interventional exercises to minimize asymmetry in athletes. These exercises then may provide a protective effect in soccer and softball players, as higher rates of asymmetries in scores has been linked with a higher risk of athlete injury. The increase in the number of players with asymmetry in scores in the basketball cohort suggests an added detrimental effect for those athletes in addition to their decreased postseason FMS™ scores.

Limitations
The sample size and lack of a control group within this study represent key limitation in the ability to detect significant patterns resulting from the implementation of the standardized exercises. A larger number of participants would have allowed for emergence of significant patterns between the subjects' sport and changes in the individual movement scores on the FMS™. Likewise, use of a control group would allow more confidence in the effectiveness of interventional exercise versus improved strength, stability and motor control specifically related to in-season training and competition alone.

The quality of exercises performed by the teams may have varied, as team captains and coaches supervised soccer players, while strength-training
staff supervised basketball and softball players. This study solely involved NCAA Division III athletes, who may have varying athletic abilities compared to their Division I or II counterparts, limiting generalizability to athletes of other divisions. Furthermore, inclusion of athletes from only three different sports further limits generalizability to athletes playing those sports not represented in this study. Similarly, differences in coaching technique and philosophy, skill acquisition and sport specific biomechanics were not taken into consideration as a possible influence in improving FMS™ scores.

Additionally, this was not a randomized, blinded study, which may influence the extent to which one may interpret these results. However, past studies have shown that, in the absence of an intervention, there are no significant differences in composite FMS™ scores over the course of certain athletic seasons.1 Thus, the statistically significant findings in this study may be compared to those results, indicating that interventional exercises may indeed change composite FMS™ scores in certain athletes. Future studies should assign corrective exercises in the context of a randomized, blinded study design, with a control group in order to attain more robust analysis regarding changes in FMS™ score or asymmetry from pre- to postseason.

Lastly, though these results provide an understanding of potential trends over the course of one season and may be applicable to other athletes, continued studies over future seasons may help determine the long-term effect of these exercises on athletes' FMS™ scores and number of asymmetries.

CONCLUSIONS
The ability to improve athlete scores through interventional exercises allows for the creation of preventative training regimens that provides practitioners an opportunity to maintain or improve athlete performance. The results of the current study suggest that a standardized interventional program implemented during certain athletic teams’ respective seasons can increase FMS™ scores and reduce asymmetries. Though more studies are warranted to address the negative effects of this standardized program in women's basketball players, this study demonstrated that the number of asymmetries significantly decreased from pre- to postseason in soccer and softball. Further research with an expanded sample size should also examine the effects of sport-specific exercises and improved standardization of performance of exercises, as well as long-term effects of such interventions.

REFERENCES


ABSTRACT

**Background and Purpose:** Researchers have used an injury risk algorithm utilizing demographic data, injury history, the Functional Movement Screen™ (FMS™) and Lower Quarter Y Balance Test™ (YBT™) scores to categorize individual injury risk. The purpose of this study was to identify if a group-based hybrid injury prevention program utilizing key factors from previous research with the addition of an individualized approach can modify the injury risk category of athletes.

**Study Design:** Cohort Study

**Methods:** Forty-four female subjects (ages 14-17) were recruited from a local high school soccer team. Pre-participation testing included demographic data, injury history, FMS™ and YBT™ to determine if each athletes' injury risk category using the Move2Perform algorithm. Post-testing took place after an eight-week exercise-based intervention program was completed. McNemar analysis was utilized to assess changes in the injury risk categories.

**Results:** A significant number of athletes (21 of 44) moved to lower risk categories at posttest ($p=0.000; Z=-3.869$). Of the 32 athletes in the High Risk category at pretest, 16 were Low Risk after the intervention ($p=0.002$).

**Conclusions:** A preseason, group injury prevention training program with individually prescribed corrective exercises, resulted in a significant number of subjects decreasing their injury risk category. The primary statistically significant decrease of injury risk category was seen in the Moderate Risk individuals moving down to Slight. There were three athletes that moved from the Substantial Risk category to Slight, however, this change was not statistically significant.

**Key Words:** Movement system, injury prevention training program, risk category

**Level of Evidence:** 2
INTRODUCTION
With over seven million students participating in high school athletics alone, the yearly occurrences of sports related injury are very high. Injuries range from one day of lost time to career limiting injuries. Potential career limiting injuries like anterior cruciate ligament tears, ulnar collateral ligament tears, and compound fractures are on the rise across the spectrum of little leaguers to professional athletes. Despite the presence of injury prevention programs, sports injuries are a continued problem with an estimated two million injuries occurring annually. While injury prevention programs like FIFA 11+, the PEP program, and SportsMetrics have been shown to decrease injury rate, they do not work for all populations or even all individuals in the population. One reason that these programs might not work in all cases is that injury risk is multifactorial and the aforementioned programs are not individualized nor comprehensive with their interventions. For example, FIFA 11+ includes a variety of running, strength, plyometric and balance exercises, but no exercises to address commonly present mobility restrictions. SportsMetrics focuses on jumping and landing mechanics, but lacks other evidence-based injury prevention interventions to address balance, core, strength and/or mobility. Since injury risk is multifactorial and each individual has unique deficits, it seems logical to individualize the interventions as much as is practical. This individualization would address additional domains, potentially resulting in a greater injury risk reduction.

Researchers have identified multiple risk factors that increase risk of injury, with previous injury being the most consistently reported risk factor. Other variables such as low or high body mass index, faulty biomechanics, core motor control deficits, and muscle flexibility deficits have also been identified as risk factors. Knee valgus with drop jump landing has been identified as another risk factor for anterior cruciate ligament tears in female athletes. To complicate matters further, each individual may possess different combinations of risk factors. Thus, group programs may spend too much time on a particular risk factor for an individual that does not possess that problem, and too little time on risk factors that are more profound for the individual thereby under or overdosing specific prevention efforts.

Identifying risk factors is beneficial in order to begin the process of prevention, however, screening for every risk factor is not practical. The Functional Movement Screen™ (FMS™) and Y-Balance Test Lower Quarter (YBT-LQ™) are two tools that have emerged in the literature as field-expedient options to capture multiple risk factors efficiently. The FMS™ is a series of tests that can screen a person’s ability to perform seven fundamental bodyweight tasks, scored on an ordinal scale from 0-3. Initial research of the FMS™ identified a cut score of ≤14 on FMS™ to be predictive of injury risk in American football players. This cut point was supported by a recent meta-analysis, which concluded that individuals scoring ≤14 had an OR of 2.74 (95% CI 1.70-4.43). Additionally, at least one asymmetry in hurdle stepping, lunging, active straight leg raising, or quadruped diagonal reaching patterns was associated with increased risk for a time-loss musculoskeletal injury in American football players and later confirmed by Mokha et al as a risk factor for potential musculoskeletal injury in Division II athletes.

Researchers have developed a computer algorithm (Move2Perform, Functional Movement Systems, Chatham, VA) that can synthesize multiple risk factors including demographic factors, injury history, and results of field-expedient tests (including the FMS™ and YBT-LQ™) to place an athlete into one of four categories according to risk level. The software algorithm further uses population specific cut points to place the athlete in the risk category. Lehr et al established a significant association between the risk category of an athlete identified by the computer algorithm and noncontact lower extremity injury in collegiate athletes. Athletes who were in
the Substantial and Moderate Risk were 3.4 times more likely to sustain an injury compared to those in Slight or Optimal groups.3

While athletes at high risk for injury may be able to be identified by the Move2Perform algorithm, the question remains if risk category can be modified. Both the FMS™ and YBT-LQ™ have been identified as modifiable with exercise. Kiesel et al27 found that utilizing a seven-week off-season intervention program, 52% of professional football players in the program were able to score above the injury cut score of 14. Individualized corrective exercises were prescribed based on each player’s specific deficit on the FMS™ and the athletes had a supervised progression of these corrections over the course of seven weeks.27 A randomized controlled trial performed by Bodden et al28 also identified the FMS™ is modifiable with the prescription of corrective exercises over a course of four and eight weeks in mixed martial arts athletes.28 The YBT-LQ™ and SEBT have also been shown to be modifiable with an exercised based program. Steffen et al29 identified a significant improvement of functional balance as tested by the SEBT in athletes who highly adhered to the FIFA 11+ program which included a 20 min warm-up consisting of 15 single exercises that focused on strength, plyometrics, agility and field balance techniques. Those athletes also were identified as having a 72% reduction of injury risk based on their improvements on the SEBT.29 Thus, FIFA 11+ appears to be effective at reducing injury risk, but may benefit from the addition of an individualized approach to further decrease injury risk.

A systematic approach to injury prevention should take the best available evidence and apply it in a logical manner. Since group injury prevention programs have been shown to decrease injury rate,30-32 it would be prudent to include the components of these programs that demonstrate effectiveness. There are also several other variations of injury prevention training protocols within the literature which include strength training, coordination, speed and agility, flexibility, balance training, and jumping. Rossler et al32 found a 46% reduction in injuries in organized youth sports with the implementation of an exercise-based injury prevention program and further identified the need for jumping/plyometric exercises being particularly relevant for the reduction. Among the 21 studies reviewed by Rossler et al,32 each study included either a progressive difficulty level that increased weekly or a continuous difficulty level which increased at each session. There are lots of variability in session time frames as some injury prevention programs included only a five-minute warm-up, while others lasted for 30 minutes. Overall, Rossler et al32 found that all injury prevention programs were significantly effective in children and adolescents with the greatest risk reduction in the sub-elite athlete.

While it appears exercise-based injury prevention programs decrease risk of injury and improve scores on functional movement and balance testing, no current research has identified if the Move2Perform injury risk category can be modified. Therefore, the purpose of this study was to identify if a group-based hybrid injury prevention program utilizing key factors from previous research with the addition of an individualized approach can modify the injury risk category of athletes.

METHODS

This study was approved by the University of Evansville’s Institutional Review Board. Fifty-four high school female soccer players were enrolled in the program over the course of three years, with forty-four athletes included in participation of the program. All players were educated on the program and testing involved. Inclusion criteria included: 14-17 years old, female, current athlete in preseason of their sport. Subjects were excluded from the program if they had a current injury or were not medically cleared to participate. Previous injury was defined as ‘any injury occurring during athletic activity resulting in medical attention and/or the removal of the player from the current session and/or subsequent time loss of at least one athletic session (match or practice) as a direct result of that injury.’26 All of the subjects were under legal age, therefore parental informed consent and release of testing information for research use was obtained in order to house athlete’s data within the Move2Perform database. Each athlete’s data was pulled from the Move2Perform database and deidentified for statistical analysis. Program design included individually prescribed corrective exercises and 14 supervised
group sessions that included jump, agility, and core training over the course of eight weeks.

**Testing**
Testing was performed on all 44 subjects at the beginning of the eight-week training session. Testing included demographic data, injury history, FMS™ and YBT™ testing which identified each athlete's injury risk category per Move2Perform algorithm. Each athlete was categorized in one of the following categories: Substantial deficit, Moderate deficit, Slight deficit, or Optimal. Each athlete was re-tested with the aforementioned protocol after they completed the eight-week training program.

**Training Sessions**
After their initial Move2Perform category was identified, each athlete received corrective exercise strategies based upon their FMS™ and YBT™ scores regardless of their category. Corrective exercise prescription was based upon the hierarchy of the Functional Movement Systems model in which deficits in symmetry, mobility, and stability were identified and ranked. Once those areas of deficit were identified each athlete received their three individualized corrective exercise strategies to perform as part of their warm-up and cool-down during the training program.

Athletes participated in an eight-week group program which included supervised sessions, two days per week. Each session consisted of each athlete’s corrective exercises, a functional warm-up based on the FIFA 11+, three 20-minute circuits that included jump training, core strengthening, and agility training, and a cool-down consisting of each athlete’s corrective exercises. The program followed a structured progression with each circuit increasing in difficulty and complexity of movement pattern over the course of eight weeks. See Appendix 1 for more detailed description of the program.

**Statistical Methods**
The primary outcome for this study was change in risk category. Significant changes in the four risk categories (Substantial, Moderate, Slight, and Optimal) were determined using a Wilcoxon Signed Ranks Test with significance set at 0.05. An additional analysis was performed using a modified risk cutoff based on the results from Lehr’s study, which condensed Moderate and Substantial categories to a single to “High Risk” category, and Slight and Optimal to a single “Low Risk” category. Change across this risk threshold was determined using a McNemar’s test, with significance set at 0.05.

**RESULTS**
Fifty-four athletes participated in pretest. Ten athletes did not complete the program due to financial constraints (four participants) or other schedule conflicts (six participants). No injuries were sustained during participation in the program, therefore forty-four athletes were included in the final analysis.

A Wilcoxon Signed Ranks test was used to determine change in risk category from pretest to posttest. Twenty-one athletes had an improved risk category (i.e. movement to a lower risk category), two athletes had decline in risk category (i.e. movement to a higher risk category), and twenty-one athletes were ties (i.e. no change in risk category). Figure 1 illustrates the movements of athletes by category at pre-test and post-test. The improvement in risk category from pretest to posttest was significant (p=0.000, Z=-3.869).

Of the forty-four athletes, thirty-two were in the High Risk (Substantial and Moderate Risk combined) category at pretest. At posttest, sixteen of the athletes in the High Risk category had moved to the Low Risk (Slight and Optimal Risk combined) category. More specifically, at pre-test there were 11 athletes in the Substantial Risk category and five remained at post-test, 21 athletes in Moderate category at pre-test and 11 remained at post-test, and there were 10 athletes in Slight category and two in Optimal category at pre-test which remained in their measured category at post-test. The results of the McNemar’s analysis revealed that the number of High Risk athletes moving to the Low Risk category was significant (p<0.000; see Table 1). Figures 2 and 3 indicate the total number of participants in each risk category at pretest and at posttest.

**DISCUSSION**
The purpose of this retrospective study was to determine if injury risk category as defined by
Move2Perform is modifiable. It has been suggested in previous research that categorizing athletes with efficient screening tools allows for prioritization of prevention strategies.4 To the authors’ knowledge, this is the first study to look at the ability to change Move2Perform injury risk category based on an injury prevention training program and/or individualized treatment. The program in this study utilized an individualized group intervention strategy, which included individualized corrective exercises based on FMS™ and YBT™ scores, jump training, agility drills and core strengthening. The results of this study showed that nearly 48% of athletes moved to a lower risk category following intervention. This finding is consistent with previous intervention studies looking at interventions to improve either the FMS™ or

Table 1. 2x2 table calculated with McNemar’s analysis demonstrating significant movement of participants in the High Risk group pretest to the Low Risk group at posttest.

<table>
<thead>
<tr>
<th></th>
<th>Pretest</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Risk</td>
<td>Low Risk</td>
</tr>
<tr>
<td>Pretest</td>
<td>16</td>
<td>16*</td>
</tr>
<tr>
<td>Low Risk</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td>28</td>
</tr>
</tbody>
</table>

* = statistically significant difference at p=0.0002

Figure 1. Participant injury risk category movement from pre-test to post-test.

Figure 2. Participant total per category at pre-test.

Figure 3. Participant total per category at post-test.
Therefore, an individualized group injury prevention program can be beneficial in not only improving performance on the FMS™ and YBT-LQ™, but may alter risk category as well.

Using Lehr's modified categories, 50% of athletes in the High Risk category moved to Low Risk at post-test. While this change is statistically significant, its clinical relevance is likely more important. Athletes in the High Risk category have been reported to be 3.4 times more likely to sustain an injury compared to their Low Risk peers per Lehr et al, there fore crossing the threshold from the High Risk to Low Risk category may decrease injury risk but this needs to be studied further. Movement within groups was primarily seen in the athletes who were in the Moderate risk category at pre-test. Sixty-two percent (13 athletes) of the Moderate Risk pre-test athletes moved into the Slight Risk category at post-test which was a statistically significant change (p<0.0001). The researchers believe this holds clinical significance as well, by demonstrating the ability for a clinician to triage the Moderate risk athletes into a group training program in order to potentially decrease their injury risk level. The clinical application would include utilizing the pre-testing protocol and injury risk categorization, then enrolling athletes that are in either the Moderate, Slight, or Optimal injury risk categorization into an individualized group training program like the one this study describes. By following that protocol at pre-season, the remaining athletes in the Substantial Risk category would be able to have more individualized assessment and treatment which would in turn lessen the burden on the clinicians triaging care.

Athletes that are categorized in Substantial Risk are in that category due to current injury, current pain, and/or substantially poor movement competency. Basic movement competency means an athlete is able to exhibit a full array of range of motion, body control and movement awareness in various postures. All three of these characteristics are major risk factors for subsequent time-loss injury. The authors hypothesized the Substantial Risk category athletes would not see enough injury risk factor reductions from implementation of a group injury prevention training program (albeit a partially individualized program) because the program was too high level for the demonstrated movement competency, and/or athletes were experiencing pain at pre-test, and/or athletes were currently injured at pre-test. There were three outliers that did move from Substantial Risk to Slight Risk category. Looking at each of those athlete's pre-test information compared to their post-test, there was not a clear pattern of why those individuals improved and others in Substantial category did not. Two of the athletes had pain at pre-test in the upper extremity that they did not report at post-test which allowed for a decrease in a significant risk factor. The other athlete was able to demonstrate improved YBT-LQ™ composite scores and cleared asymmetries within the FMS™ which allowed for movement to a lower risk category. The movement between categories of those three athletes was not statistically significant. Future research with a larger sample size may shed more light on if an individualized group training program does in fact modify the Substantial Risk athlete's category similarly to the decrease seen in the Moderate Risk group. At this time the authors' recommendation for the Substantial Risk athlete's care would be to have more formalized assessment of the risk factors causing the athlete to be rated as substantial and then for each athlete to receive individualized treatment.

There were a few limitations identified by the authors. One limitation of this study is the lack of control group, which precludes a clear cause/effect relationship as no randomization occurred. Thus, it also cannot be determined the relative contribution of each of the parts of the intervention to changing risk category. A second limitation was a lack of control of co-interventions which may have influenced the outcomes of the study. Although the authors have no reason to believe this impacted the results of the study, the participants may have received additional interventions such as personal training, weight lifting, massage and/or chiropractic care. There also was no short-term or long-term follow-up to identify if the change in injury risk category was maintained over time. And finally, due to the retrospective nature of this study, full demographic data (height and weight) on the participants was not obtained. Additional research should focus on the maintenance of injury risk categories and the actual injury risk reduction occurred once an individual's category has been modified.
Although the specific results of this study cannot be generalized beyond the population tested, matching Moderate, Slight and Optimal Risk category athletes with a standard individualized group injury prevention program appears to do no harm and significantly benefit those in the Moderate Risk category. Matching the Substantial Risk category athletes with an individualized treatment program may also allow ideal allocation of available resources in the high school athletic training room to the individuals that need it the most. Therefore, it will be beneficial to perform additional studies with a larger sample size to increase the external validity as well as confirm the broad use of this injury prevention method.

CONCLUSIONS
The results of the current study indicate that an athlete’s injury risk category can be altered; however, the strategy to implement is dependent on the athlete’s initial risk category. Group injury prevention training programs can be utilized to change the injury risk category in athletes who are categorized as either Optimal, Slight or Moderate, but a more individualized approach may be needed for athletes that fall in the Substantial risk category. Utilizing the Move2Perform algorithm can be beneficial during pre-participation physicals to identify an athlete’s injury risk category and also provide a good filtering system for utilization of injury prevention resources.

REFERENCES


ABSTRACT

Background: Non-arthritic hip pain is defined as being related to pathologies of the intra-articular structures of the hip that can be symptomatic. A trial of non-operative management is commonly recommended before consideration of surgery for individuals with non-arthritic hip conditions. There is a need to describe a non-operative or conservative treatment plan for individuals with non-arthritic hip pain.

Purpose: The purpose of this literature review was to systematically examine the literature in order to identify and provide evidence for non-operative or conservative management of individuals with non-arthritic hip pain. A proposed home exercise program will be provided for individuals with non-arthritic hip pain.

Study Design: Review of the Literature.

Materials/Methods: A literature search of PubMed, Medline, SPORTSDiscus, and CINAHL was conducted. Keywords included: “hip” AND “femoroacetabular impingement” OR “labral tear.” Studies were included if they described non-operative management for individuals with non-arthritic hip pain. Studies were excluded if they recommended a trial of conservative treatment without specific management or interventions and/or activity modification without specific details for intervention.

Results: A total of 49 studies met the eligibility criteria and were included in the review. Rehabilitation recommendations were identified from manuscripts including clinical trials, case series, discussion articles, or systematic reviews related to the non-operative or conservative management of non-arthritic hip pain. Rehabilitation interventions focused on patient education, activity modification, limitation of aggravating factors, an individualized physical therapy protocol, and use of a home exercise program.

Conclusions: Rehabilitation should address biomechanical deficiencies with neuromuscular training of the hip and lumbopelvic regions. While the current literature on non-operative management is limited, future randomized control trials will establish the effectiveness of specific physical therapy protocols for individuals with non-arthritic hip pain.

Level of Evidence: 3b

Key Words: FAI, acetabular labral tears, dysplasia, structural instability, movement system
INTRODUCTION
Non-arthritic hip pain is described as being related to pathologies of the intra-articular structures of the hip that can cause pain including femoroacetabular impingement (FAI), dysplasia, structural instability, acetabular labral tears, chondral lesions, and ligamentum teres tears. These conditions primarily occur from microtrauma associated with dynamic movement between the proximal femur and the acetabulum. When left unaddressed, FAI, dysplasia, and structural instability can lead to the progression of acetabular labral tears, chondropathy, and potentially osteoarthritic change. Arthroscopic surgical procedures to address structural abnormalities, decrease pain, and improve function have significantly increased over the past decade. However, a recent systematic review found that there is a high prevalence of structural deformities in asymptomatic individuals. Additionally, musculoskeletal impairments such as strength deficits associated with non-arthritic pathology are not necessarily addressed with surgery. Deficiencies in the surrounding hip region musculature may lead to joint instability and excessive motion contributing to structural damage, pain, and decreased function. It may be possible to decrease intra-articular stresses in the presence of structural abnormalities, through management of muscular deficiencies and avoid the need for surgical correction. An evaluation algorithm and treatment classification has been outlined to identify those with non-arthritic hip conditions that might benefit for a prioritized non-operative treatment program.

A trial of non-operative management is commonly recommended before consideration of surgery, however specific interventions remain a point of controversy. Considering that not all individuals will benefit from surgical intervention and the possibility for management of extra-articular deficiencies to relieve symptoms, a non-operative or conservative treatment plan needs to be described for non-arthritic hip pain. The purpose of this literature review was to systematically examine the literature in order to identify and provide evidence for non-operative or conservative management of individuals with non-arthritic hip pain. A proposed home exercise program will be provided for individuals with non-arthritic hip pain. The information attained will assist clinicians in making treatment decisions based on the current standard of care for management of non-arthritic hip conditions.

METHODS
A search of the PubMed, Medline, SPORTSDiscus, and CINAHL databases was conducted to include articles from 1997 until July 2017. Manuscripts were identified that presented clinical trials, case series, discussion articles, or systematic reviews for non-operative or conservative management of non-arthritic hip pain. The search excluded single series case reports, abstract-only publications, and editorial commentary. The following key words were used in combination for searching the electronic databases: "hip" AND "femoroacetabular impingement" OR "labral tear."

The literature search included research articles if they met the following criteria: 1) written in English, 2) published in a peer-reviewed journal from 1997 until August 2017, and 3) described non-operative or conservative management for individuals with non-arthritic hip pain. Studies were excluded if they recommended a trial of conservative treatment without specific management or physical therapy interventions and/or activity modification to avoid extreme ranges of motion without specific details for intervention. The primary author reviewed the abstracts of all references retrieved from the search and duplicates were removed. From this search, full length publications were retrieved, and the reference lists of these articles were reviewed for any additional relevant manuscripts.

RESULTS
The initial search identified a total of 2,147 research articles. After applying the inclusion/exclusion criteria and performing an independent search of reference lists, a total of 49 studies met the eligibility criteria. Overall, there were 35 articles addressing FAI, four articles addressing acetabular labral tears, one article addressing dysplasia or structural instability, and nine articles addressing a combination of FAI, acetabular labral tears, dysplasia, structural instability, chondral lesions, and/or ligamentum teres tears as shown in Figure 1.
Thirty-two of the articles were review and/or discussion studies, seven were experimental studies, and ten addressed feasibility (pilot) and protocol studies for future randomized controlled trials. These articles were categorized per their level of evidence based on the 2009 guidelines from the Oxford Center of Evidence-Based Medicine. Further evaluation of each article was performed for quality of evidence based on the established Grading of Recommendations Assessment, Development and Evaluation (GRADE) system with classification of studies as: “high quality”, “moderate quality”, “low quality”, or “very low quality.” The discussion and review articles were principally constructed on expert opinion Level 5 evidence, with the systematic reviews utilizing Level 2a and 3a evidence in order to analyze the experimental studies performed on individuals with non-arthritic hip pain. The expert opinions established in these discussion and review articles were classified as “very low quality” due to the uncontrolled nature of clinical observations.

Of the 32 review and discussion articles: 24 addressed FAI, three addressed acetabular labral tears, one addressed dysplasia or structural instability, and four addressed a combination of FAI, acetabular labral tears, and dysplasia or structural instability. These articles provided comprehensive non-operative management recommendations, a synthesis of which is provided in Table 1. Of the seven experimental studies: three addressed FAI and four addressed a combination of FAI, acetabular labral tears, dysplasia or structural instability, chondral lesions and/or ligamentum teres tears. Of these these four were case series (three prospective and one retrospective), one was a prospective clinical outcomes study, one was a retrospective matched analysis study, and one a descriptive epidemiological study. Detailed descriptions of these studies are found in Table 2. Of the 10 articles addressing future randomized controlled trials: eight were established for patients with symptomatic FAI and two were established for patients with intra-articular hip pain, including FAI, acetabular labral tears, and structural instability/dysplasia. Details pertaining to the specific study design, methodology, and results for the six protocol studies and four feasibility studies are provided in Table 3. No randomized control trials were identified.

Table 1. Recommended Therapeutic Interventions from Review and Discussion Articles.

<table>
<thead>
<tr>
<th>Therapeutic Interventions</th>
<th>Number of Articles (out of 32)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip musculature strengthening</td>
<td>22</td>
</tr>
<tr>
<td>Pelvic stability/posture (pelvic inclination)</td>
<td>16</td>
</tr>
<tr>
<td>Core muscle strengthening</td>
<td>14</td>
</tr>
<tr>
<td>Neuromuscular training</td>
<td>13</td>
</tr>
<tr>
<td>Hip muscular stretching/flexibility</td>
<td>12</td>
</tr>
<tr>
<td>Manual therapy interventions</td>
<td>12</td>
</tr>
<tr>
<td>Dynamic biomechanical control</td>
<td>10</td>
</tr>
<tr>
<td>Gait training</td>
<td>4</td>
</tr>
<tr>
<td>Study</td>
<td>Type of Study (Quality of Study)</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Emara et al. 2011</td>
<td>Prospective case series (Low)</td>
</tr>
<tr>
<td>Feeley et al. 2008</td>
<td>Descriptive epidemiologic study – NFL athletes (Very Low)</td>
</tr>
<tr>
<td>Hunt et al. 2012</td>
<td>Prospective observational clinical outcomes study (Low)</td>
</tr>
<tr>
<td>Jager et al. 2004</td>
<td>Prospective case series (Very Low)</td>
</tr>
<tr>
<td>Reynolds et al. 1999</td>
<td>Retrospective case series (Very Low)</td>
</tr>
<tr>
<td>Spencer-Gardner et al. 2017</td>
<td>Retrospective matched paired analysis (Low)</td>
</tr>
<tr>
<td>Yazbek et al. 2011</td>
<td>Prospective case series (Low)</td>
</tr>
</tbody>
</table>

M – male; F – female; FAI – femoroacetabular impingement; ER – external rotation; ABD – abduction; EXT – Extension; FLEX – flexion; IR – internal rotation; HHS – Harris hip score; VAS – visual analog scale; LT – acetabular labral tear; CT - computerized tomography; BMI – body mass index; HA – hip arthroscopy

* Quality of evidence based on the GRADE classification system.
Table 3. Studies Addressing Future Randomized Controlled Trials in Individuals with Non-Arthritic Hip Pain.

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of Study (population)</th>
<th>Number of Patients (participants)</th>
<th>Diagnosis (treatment)</th>
<th>Hypothesis/Results</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boye et al. 2015</td>
<td>Feasibility (admission)</td>
<td>75 (33 and 22 from two separate centers)</td>
<td>FAI - hip pain</td>
<td>ARTHROSCOPIC SURGERY VS. NON-SURGICAL MANAGEMENT</td>
<td>Sufficient patient accrual for a randomized trial of FAI treatment is currently feasible while equipoise still exists among patients and surgeons.</td>
</tr>
<tr>
<td>Cappel et al. 2016</td>
<td>Protocol (male military)</td>
<td>100 (male military participants)</td>
<td>intra-articular non-arthritic hip pain</td>
<td>7-day residential intervention vs. 8 PT led, out-patient treatments (over 6 weeks) combined with home exercise program</td>
<td>Presents the protocol for a RCT that will compare the effects of a residential intervention with conventional outpatient care on pain and physical function in young patients with non-arthritic hip pain.</td>
</tr>
<tr>
<td>Griffin et al. 2016 (1)</td>
<td>Feasibility (admission)</td>
<td>42 out of 60 eligible (from 9 hospital centers)</td>
<td>FAI - hip pain</td>
<td>Arthroscopic surgery vs. conservative care</td>
<td>-Diagnostic and recruitment consultations in 60 patients were used to develop a model for an optimal recruitment consultation. -The Hip Outcome Tool (HOCT) at 12 months was identified as an appropriate outcome measure. -Estimated the sample size 344 participants (from 25 centers/18 months).</td>
</tr>
<tr>
<td>Griffin et al. 2016 (2)</td>
<td>Protocol</td>
<td>349 (over a 26-month recruitment period in 24 hospital centers)</td>
<td>FAI - hip pain</td>
<td>Arthroscopic surgery vs. conservative care (clinical cost effectiveness)</td>
<td>Primary Outcome: Pain and function assessed by HOCT-33 measured at 1 year. Secondary Outcome: General health (SF-12), quality of life (EQ-5D-3L) &amp; pt. satisfaction.</td>
</tr>
<tr>
<td>Harris-Hayes et al. 2016</td>
<td>Feasibility (admission)</td>
<td>35 (18 treatment, 17 control from Washington University)</td>
<td>Chronic hip joint pain</td>
<td>Movement pattern training (MPT) vs. wait-list control (no treatment)</td>
<td>Primary Outcome: Retention rates did not significantly differ between MPT (89%) and control groups (94%). -1618 patients (89%) in the MPT group attended at least 80% of the control studies and performed their home program at least once per day.</td>
</tr>
<tr>
<td>Mansell et al. 2016</td>
<td>Protocol</td>
<td>80 from Madigan Army Medical Center (over 2 years)</td>
<td>FAI (with and without acetabular labral tear)</td>
<td>Arthroscopic decompensation vs. non-surgical rehabilitation</td>
<td>Primary Purpose: Determine if there is a difference in self-reported functional outcomes between arthroscopic surgery and supervised physical therapy intervention in patients with symptomatic FAI. Secondary Purpose: Evaluate the differences in hip-related healthcare utilization and associated costs.</td>
</tr>
<tr>
<td>Palmer et al. 2014</td>
<td>Protocol</td>
<td>120 (over 24 months from NHS clinics in at least 3 hospitals)</td>
<td>FAI - hip pain</td>
<td>Surgical management vs. non-surgical management</td>
<td>Primary Objective: Determine whether arthroscopic surgery or PT and activity modification is more effective in improving symptoms and preventing the progression of osteoarthritis in patients with symptomatic FAI. Secondary Objective: Compare cost effectiveness of physiotherapy and activity modification with arthroscopic surgery.</td>
</tr>
<tr>
<td>Srocchum et al. 2017</td>
<td>Feasibility (admission)</td>
<td>23 out of 30 eligible (from a single NHS acute hospital in Devon, England)</td>
<td>FAI - hip pain</td>
<td>-PPT vs. routine care -PPT at 3-months of specialist physiotherapy led care</td>
<td>Primary Outcome: Improvement of symptoms: NAHS, HAGOS, OHS, and HADS.</td>
</tr>
<tr>
<td>Wall et al. 2016 (3)</td>
<td>Protocol (personal therapy)</td>
<td>13 randomized out of 42 (from the UK FASHION trial)</td>
<td>FAI - hip pain</td>
<td>Rehabilitation led by physiotherapist: (1) Detailed patient assessment (2) Education and advice (3) Help with pain relief (4) Individualized exercise program</td>
<td>Primary Outcome: PHT provides a structure for the non-operative care of FAI and offers guidance to clinicians and researchers.</td>
</tr>
<tr>
<td>Wright et al. 2016</td>
<td>Feasibility (admission)</td>
<td>15 out of 18 eligible (from a single surgeon practice from the Department of Orthopedic Surgery, Wake Forest Baptist Medical Center)</td>
<td>FAI - hip pain</td>
<td>Combination of manual therapy and supervised exercise (with advice and home exercise) vs. advice and home exercise -Both groups both of which groups improved a mean of 17.6 mm and 18.0 mm for the advice and home group.</td>
<td>Primary Outcome: Supervised manual therapy did not result in greater improvement in pain or function compared to advice and home exercise.</td>
</tr>
</tbody>
</table>

FAI = femoroacetabular impingement; UK = United Kingdom; NHS = National Health Service; HOCT = Hip Outcome Tool; HOCT-33 = Hip Outcome Tool 33; RCT = randomized control trial; PRO’s = patient reported outcomes; LT = acetabular labral tear; HOS = Hip Outcome Score; GROC = Global rating of change; NPRS = Numeric pain rating scale; ADL = activities of daily living; NAHS = non-arthritic hip score; HAGOS = hip and groin outcome score; OHS = Oxford hip score; HADS = hospital and anxiety depression scale; MRI = magnetic resonance imaging; VAS = visual analog scale; LEFS = lower extremity functional score; PT = physical therapy.
Rehabilitation interventions throughout the identified studies including patient education, activity modification, limitation of aggravating factors, performance of an individualized physical therapy protocol, and performance of a home exercise program, have been shown to decrease pain and improve function in patients with non-arthritic hip pain. Interventions should focus on addressing neuromuscular deficits with rehabilitation of the hip and lumbopelvic regions. Exercise suggestions gleaned from the included studies were used to generate a proposed home exercise program for individuals with non-arthritic hip pain are presented in Appendix A.25

DISCUSSION
This literature review identified studies related to non-operative or conservative care in the treatment of individuals with non-arthritic hip pain. Discussion and/or review articles, experimental studies, and randomized control feasibility and protocol studies addressing management of individuals with FAI, acetabular labral tears, dysplasia, structural instability, chondral damage, and ligamentum teres tears were evaluated. From these studies, several concepts were identified that should be considered when beginning all non-operative management plans including: patient education,26-28 symptom control (with the use of non-steroidal anti-inflammatory drugs),29-32 identification of aggravating activities,31,33 modification of these activities with a focus on limiting extreme ranges of motion,29-31,34,35 and initiation of therapeutic interventions within a physical therapy protocol.33,36,37 Therapeutic interventions should consist of addressing neuromuscular deficits with training of the hip and lumbopelvic regions.

Physical therapy interventions that were described in the discussion and/or review articles included: hip musculature strengthening (specifically the hip abductors and deep external rotators);3,26,29,30,32,34,36,38-52 pelvic positioning and stability related to posture;29,30,33,34,36,38,43,44,46-51,53,54 core muscle strengthening;29-31,33,34,37,38,40,43,45,46,53,55,56 neuromuscular training focused on hip and lumbopelvic stability;1,3,34,35,37,38,42,43,45,46,48,50-52,54 stretching and flexibility for the surrounding hip musculature;1,3,34,35,37,38,42,45,46,50-52,54 inclusion of manual therapy interventions focusing on soft-tissue mobilization of surrounding structures of the hip;32,34,41,42,43,45-47,50,51,54,57,58 dynamic biomechanical control including proprioception, balance, and coordination training;3,37,38,41,42,43,45-48,52 and gait training to address pathological adaptations with use of orthotics if necessary.27,40,50,52 It is recommended that all physical therapy interventions should be prescribed and performed on an individualized basis.

The goal of rehabilitation should be to establish dynamic stabilization of the surrounding hip musculature and concurrent core and pelvic control to prevent accessory motion of the hip joint during complex activities.34,50 Neuromuscular training of the hip and lumbopelvic regions is important for establishing motor control during sports-related activities.50,51 Of note, the discussion and review articles were principally constructed on expert opinion (Level 5 evidence), with the systematic reviews utilizing Level 2a and 3a evidence in order to analyze the experimental studies performed on individuals with non-arthritic hip pain.23 Recommendations in the current literature review are based on “low” or “very low quality” evidence due to the uncontrolled nature of the clinical observations.24

The experimental studies included in this literature review include Level 4 (case series & descriptive epidemiological study), Level 2b (retrospective matched analysis), and Level 2c (clinical outcomes study) evidence, for the use of non-operative management of individuals with FAI, dysplasia, and structural instability. Three case series (two prospective59,60 and one retrospective61) specifically addressed management of individuals with the diagnosis of FAI. While two of these studies60,61 did not specifically define the non-operative management plan that was utilized, Emara et al.59 demonstrated a successful plan utilizing four stages of conservative treatment that included: avoidance of physical activity with symptom control during the acute stage, physical therapy with stretching exercises for two to three weeks, assessment of normal hip ROM, and modification/adaptation of ADL’s. Prolonged sitting during this time frame was avoided, but if necessary it was recommended that individuals lean backwards periodically to decrease hip flexion and elicitation of impingement causing posture.59 Thirty-three of the 37 patients (89%) had positive results from the conservative management plan with both...
the mean Harris Hip Score and non-arthritic hip scores improving from 72 to 91 (out of 100) over a 24-month period and visual analog scores for hip pain decreasing from 6 to 2 over the same timeframe.59 The results of this case control study suggests that an intervention focused on activity modification and physical therapy can significantly improve hip function and decrease symptoms in individuals with FAI.

Three experimental studies addressed non-operative management of intra-articular disorders including FAI, acetabular labral tears, dysplasia, chondral lesions and ligamentum teres partial tears.27,28,62 Two of these studies provided specifics of non-operative management including the case series by Yazbek et al.28 demonstrating a decrease in pain, improvement in functional movement, and increased lower extremity muscular balance in four individuals. This was achieved by correcting abnormal joint movement by emphasizing muscular strengthening and sensory motor training. When the muscle imbalance was corrected, the participants were progressed to a sports-specific functional training regimen and successfully returned to activity over a 12-week period.28 The case series performed by Hunt et al.27 demonstrated a successful management plan in 23 of 52 (44%) individuals with FAI, LT, and dysplasia over a 12-week period. All participants were taken through an individualized physical therapy protocol that emphasized femoral head motion by decreasing the anterior glide within the acetabulum through muscle training and postural positioning of the pelvis.27 This study included a home exercise program but did not comment on the specifics beyond modification and avoidance of everyday aggravating activities. As shown in Table 2, four of the experimental studies were classified as having “low quality” and three as having “very low quality” of evidence.

Level 1 randomized controlled trials (RCT) are the type of study that will establish “high quality” evidence for the cause and effect analysis of non-operative management for individuals with non-arthritic hip pain. While the current literature review did not identify any completed RCT’s to date, several feasibility and protocol studies were available in the literature. The five feasibility studies provided in this review demonstrate that a sufficient accumulation of patients, physical therapists, and surgeons willing to participate in future RCTs comparing: surgical vs. non-surgical management of FAI,63,64 movement pattern training (MPT) vs. no treatment for intra-articular, non-arthritic hip pain,65 physical therapy vs. self-management of FAI,66 and a combination of manual therapy, physical therapy, and home exercise vs. advice and home exercise for FAI.67 While feasibility studies demonstrate the willingness for participation; protocol studies serve to define the intended treatment and control populations, methodology, and study design. They also establish the intended hypothesis or objectives that the future RCTs would pursue. Four protocol studies were identified in this review, with three describing the comparison of surgical vs. non-surgical management of FAI68-70 and a seven-day in-patient intervention vs. physical therapist led, outpatient intervention with home exercise program, for individuals with intra-articular, non-arthritic hip pain.71

A study conducted by Wall et al.25 established a suggested rehabilitation protocol based off of a prior feasibility study.64 and a protocol study.68 The Personalized Hip Therapy (PHT) protocol provides the specific non-operative management that will be utilized in the FASHIoN RCT.25 The authors identified four rehabilitation components that were to be utilized in their future RCT including: a detailed patient assessment, education and professional advice, symptom control and pain relief, and an individualized exercise-based program.25 Optional, individualized management was also included for treatment of coexisting symptoms, use of orthotics for biomechanical abnormalities, use of corticosteroid injections for patients with severe pain, and manual therapy interventions.25 A home exercise program will be provided for each individual participating in the non-operative group of the RCT.

This literature review has attempted to assimilate the current evidence for use of non-operative or conservative care for individuals with non-arthritic hip pain and suggest an exercise program. The information provided herein may benefit clinicians in making treatment decisions based on the current peer-reviewed literature. The provided home exercise program reflects the author’s compilation of exercises utilized within the peer-reviewed literature
and could be performed along with an individualized rehabilitation protocol. There are limitations to this proposed home exercise program that need to be considered when applying the information presented. The proposed rehabilitation interventions and compiled home exercise program are based on the authors interpretation of the current peer-reviewed literature. These recommendations may not be the only viable options for non-operative management of individuals with non-arthritic hip pain. No cause and effect relationships between the proposed exercises and outcomes can be inferred.

CONCLUSIONS

In general, the results of this literature review indicate that rehabilitation intervention focused on patient education, activity modification, limitation of aggravating factors, an individualized physical therapy protocol, and a home exercise program, can decrease pain and improve function in patients with non-arthritic hip pain. Interventions should focus on addressing neuromuscular deficits with training of the hip and lumbar-pelvic regions. While the current literature on non-operative management is limited, future randomized control trials will establish the effectiveness of specific physical therapy protocols for individuals with non-arthritic hip pain.

REFERENCES


Exercise 1: Standing Hip Abduction

- Stand with feet together.
- Squeeze both gluteus muscles and lift leg with knee bent at a 45° angle.
- Maintain core, pelvis, and shoulder alignment without allowing any movement of your pelvis.
- Move the lifted leg away from midline, by rotating outward.
- Maintain a contracted gluteus muscle and the standing knee over the second toe.
- Hold for 3 seconds.
- Perform on both sides.

Exercise 2: Mini-Lunge

- Start with a wide stance.
- Lunge forward keeping the lunging knee over the second toe.
- Do not bend the knee past the front of the toes.
- Hold for 5 seconds.
- Perform on both sides.

Exercise 3: Side Lunge

- Start with the feet shoulders width apart.
- Lunge to the side without shifting the hip or trunk, return.
- Maintain an upright core with a straight back position.
- Perform on both sides.

Exercise 4: Wall Slides

- Stand with the back against a wall and feet 18 inches from the wall.
- Slide down so that knees are slightly bent (~45°-60°).
- Do not go past 90° of knee flexion and keep the knees over the second toes.
- Hold for 15 seconds.
Exercise 5: Single leg balance

- Stand with the non-affected leg towards and touching the wall, with feet shoulders width apart.
- Lean against a wall with the non-affected leg lifted to 90°.
- Isometrically press the non-affected leg against the wall.
- Balance on the affected leg with knee slightly bent and knee over second toe.
- Hold for 5 seconds.

Exercise 6: Eccentric Hamstring Stretch

- Stand on the affected leg with knee slightly bent and arms out to side.
- Maintain a straight back and lean forward.
- Extend the hip and knee trying to keep body parallel with the floor.
- Hold for 3 seconds.
- Slowly return to starting position.
- Perform on both sides.

Exercise 7: Side-to-Side Walk

- Perform a side-to-side walk with comfortable stance.
- Step width should maintain a balanced trunk and upper extremities.
- Do not overextend laterally.
- Maintain slightly bent knees (~45°-60°).
- Perform in both lateral directions for 15 feet.

Exercise 8: Step-Down

- Stand on stool or raised surface.
- Maintain a straight back with unaffected leg off the stool or raised surface.
- Allow unaffected leg to drop until the heel touches the ground by bending the hip and knee, return.
- Keep the knee over the second toe.
- Return to starting position.
Exercise 9: Single Leg Squat

- Stand on the involved leg with back straight and opposite knee bent to 90°.
- Slightly bend the involved knee (~45°-60°) while keeping the knee over the second toe.
- Return to starting position.

Exercise 10: Hip Flexor Stretch

- Kneel on floor with a straight back.
- Lean forward until a stretch is felt in the front of the back leg/hip.
- Do not let knee go in front of the toes.
- Hold for 5 seconds.
- Perform on both sides.

Exercise 11: Hip Extensions

- Begin on hands and knees.
- Maintain a straight back and contracted core.
- Extend leg while contracting gluteus muscles.
- Do not arch the back or lift the pelvis.
- Hold for 5 seconds.
- Perform on both sides.

Exercise 12: Bridge

- Lay on the ground with knees flexed.
- Lift hips as high as possible while maintaining a contracted core and gluteus muscles.
- Hold for 5 seconds.
- Lower to starting position.
ABSTRACT

Background and purpose: Rotator cuff (RC) tendinopathy is a common disorder affecting many individuals, both in athletic and sedentary settings. Etiology of RC pathology or the most effective conservative treatment are not totally understood. The Mechanical Diagnosis and Treatment (MDT®) method is a widely known rehabilitative technique that allows therapists to diagnose and treat spinal, and peripheral mechanical disorders. Therefore, the purpose of this clinical commentary is to briefly describe RC tendinopathy, and its management using the MDT® method.

Description of topic: RC tendinopathies are often named with several different terms, showing the difficulty related unambiguous terminology and the diagnostic process. Pathologies at the glenohumeral joint are mostly labeled according to anatomy or the impaired tissues rather than in a functional way. MDT® examination allows mechanical disorders of the shoulder to be classified into categories that show good outcomes when treated accordingly.

Relation to clinical practice: The MDT® method may offer a practical, inexpensive, and effective solution to management of RC tendinopathies that present with a mechanical component.

Level of evidence: 5

Key words: McKenzie®, rehabilitation, shoulder.

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BACKGROUND AND PURPOSE
Rotator cuff (RC) tendinopathy is a very common problem of the shoulder complex, being the third most common musculoskeletal complaint, with poor long-term outcomes. Traditionally, the term tendinopathy indicates an unspecific tendon condition characterized by pain and impaired function as a result of improper tendon healing processes. The etiology of RC tendinopathy is not fully understood, and often there are imaging signs of tendinopathy in the absence of pain and/or functional deficits, making it difficult to precisely diagnose in a patho-anatomical manner. General orthopaedic tests and imaging sometimes have poor reliability, complicating the process of diagnosis, and treatment. A clinical interpretation system for RC tendinopathies based on a non-anatomical classification as described by McKenzie and May may help clinicians better discriminate those patients who may benefit from mechanically-based treatments. Therefore, the purpose of this clinical commentary is to briefly describe RC tendinopathy, and its management using the MDT® method.

BASIS OF ROTATOR CUFF TENDINOPATHY
RC tendinopathy etiology is still under debate, however, currently it is thought to develop when excessive loads exceed the healing capacity of tendon cells, with the tendon failing to repair properly. Intrinsic factors such as: age, vascularization, genetic components, and extrinsic factors such as: anatomical/biomechanical problems, capsule tightness, muscle strength deficits, abnormal scapular kinematics, and posture have been theorized as contributors to development of RC tendinopathy. With the development of RC tendinopathy, there are biochemical changes that occur in both the tendon cell population and the extracellular matrix. The typical changes include: an increased number of more elongated tenocytes, thinning of collagen fibers, hyaline degeneration, chondroid metaplasia, fatty infiltrations, and an increased ratio of type III/type I collagen. It appears that inflammatory cells are minimally present or may be absent in chronic tendon conditions.

DIFFICULTIES WITH DIAGNOSIS OF RC TENDINOPATHY
Specific patho-anatomical diagnoses are often utilized when dealing with people with RC tendinopathy. However, since not all shoulder conditions can be classified with a patho-anatomical diagnosis and as a great variety of structures may concomitantly be involved, the reliability of making such specific structural/anatomical diagnosis regarding the glenohumeral joint is poor. Clinical and special tests generally employed to establish diagnoses have limited validity, and there are a growing number of researchers who suggest that imaging findings should be cautiously taken into account in the process of diagnosis making. Moreover, there is no documented correlation between anatomical diagnostic labels and improved clinical outcomes.

Some authors have gone beyond attempts at a patho-anatomic diagnosis and suggested a mechanical classification where interventions can be properly tailored as already successfully demonstrated in other peripheral joints.

MECHANICAL DIAGNOSIS AND TREATMENT APPROACH
The Mechanical Diagnosis and Treatment (MDT®) method (also known as the McKenzie® method) proposes a mechanical classification system based on patient history, symptoms monitoring, and response to repeated movements/maintained postures. Based on the MDT® assessment, individuals with disorders involving the extremities are classified into mechanical syndromes named: 1. Derangement 2. Dysfunction 3. Postural 4. Other.

Derangement syndrome is theoretically caused by displacement of tissues that disrupt the normal resting position and the physiological biomechanics of a joint. This presents with a constant or intermittent pain and with mechanical signs that rapidly change during examination. A directional preference is identified when movement in a specific direction (may be more than one) improves patient symptoms and mechanical signs.

Dysfunction syndrome presents with intermittent signs and symptoms attributable to loading and/or stretching of impaired tissues, for example: scarring, adherence, or faulty tissue repairs. Symptoms abate as loading is removed and structural changes are observed in the long period. In the extremities, dysfunction syndrome can be further divided into articular, and contractile dysfunction syndromes.

Articular dysfunction syndrome is determined by restricted active (AROM) and passive range of motion (PROM), with symptoms emerging at end range of motion (E-ROM),
but not with resisted movements. Pain is therefore pro-
duced at E-ROM and abolished as soon as the joint is
brought back to resting position.\textsuperscript{19} Pathology is classified
as \textit{contractile dysfunction syndrome} when pain is elicited
during the arc of motion, with a substantially preserved
ROM. Symptoms tend to arise with mid-range resisted
movements and muscle elongation. In the short term,
responses to movement repetitions are neither better nor
worse.\textsuperscript{19}

\textit{Postural syndrome} occurs when there are signs due to
loading of healthy soft tissue that quickly subside as soon
as loading is removed. Pain is therefore intermittent, pro-
duced only by prolonged end-ranges postures that eases
when the end-range position is avoided. The physical
examination is normal and pathology is absent in postural
syndrome.\textsuperscript{67,72}

In case when the MDT® evaluation does not help fit the
clinical presentation within any of the aforementioned
classification categories, the case falls into the “other”
category. This includes, for example: acute trauma,
post-surgery, inflammatory pathologies, and other
conditions.\textsuperscript{19,67,72}

According to a given MDT® classification, a specific exer-
cise strategy is indicated.

\textbf{RC TENDINOPATHY IN THE MDT® ASSESSMENT
AS A CONTRACTILE DYSFUNCTION}

Since the key concept in contractile dysfunction is the
impaired muscle-tendon healing or repair, testing pro-
cedures should focus on stressing those tissues through
mechanical loading, for example in the form of isomet-
ric, concentric/eccentric contractions, and/or stretching.
Patients with RC contractile dysfunction syndrome are
mainly either young athletes or workers in their fifties or
older, who frequently perform repetitive shoulder move-
ments. A specific event is not generally recognized as a
reason of pain\textsuperscript{5} although the contractile dysfunction may
be caused by a previous trauma, an inflammatory pro-
cess, or a degenerative process.\textsuperscript{19}

On physical examination A ROM and P ROM are typically
preserved while pain is intermittent and absent at rest.
A ROM, resisted movements and muscle-tendon stretch-
ing produce pain that easily subsides when shoulder rests.
Repeated movements do not improve pain and ROM in
the short term as the remodeling process in the contract-
tile dysfunction requires time to complete.\textsuperscript{73-75}

During examination it is key to identify the target zone (if
any) that basically corresponds to the most painful point
through the arc of motion and at what point during that
movement the pain is the highest. Commonly, the most
affected movements result to be shoulder abduction/
scapular plane abduction specifically between $60^\circ$ and
$120^\circ$.\textsuperscript{78} However, internal and external rotation or a com-
bination of shoulder movements may also be affected.\textsuperscript{67}

\textbf{MDT® AS AN INTERVENTION FOR RC
TENDINOPATHY.}

Since controlled loading facilitates remodeling of dys-
functional tissues,\textsuperscript{77-82} progressively loaded exercise
programs for shoulder contractile dysfunction are advo-
cated.\textsuperscript{19,83} Programs should be selected for the symptom-
atic movement(s), with the aim of provoking pain that
abates upon cessation of exercise. Conventionally, pro-
cgrams include loads that are applied progressively from
a static to a dynamic manner through isometric, concen-
tric, and eccentric training.\textsuperscript{83,84}

A typical MDT® exercise program for shoulder contractile
dysfunction starts with 10 to 15 resisted isometric contrac-
tions every two hours in the target zone or at several angles
of the movement if the pain is felt throughout the entire
arc of motion as it is beneficial only at the angle where
performed.\textsuperscript{85} (Figure 1) If the target zone is too painful,
contractions can initially be applied near the target zone.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{isometric_contraction}
\caption{Isometric contraction in the target zone.}
\end{figure}
Sessions are then progressed to concentric training in the target zone (if any) as pain during isometric exercise improves. Otherwise, if there is not a target zone, concentric training is performed through the entire arc of motion, with light weight or an elastic resistance in the later stages. Concentric training is accomplished by abducting the involved arm (with resistance) starting from the side (Figure 2A) up to the final position (Figure 2B) where an operator removes the resistance for a new contraction. Alternatively, the subject can take off the weight with the free hand. According to symptomatic response, parameters such as: number of contractions, number of sets, angles speeds, and loads may be adjusted.

Eccentric training is eventually employed when concentric contractions with resistance no longer provoke symptoms. The intent is to help healing, fiber remodeling, and to limit recurrence. Therapeutic exercise may be applied limited to the target zone or over the entire arc of motion with a light weight in the later stages. Eccentric training is accomplished by slowing down adduction of the involved arm with resistance (in this case, elastic resistance is depicted) from an initial abducted position (Figure 3A) to the side of the subject (Figure 3B). Then an operator removes the resistance for a new contraction or the subject can take off the weight/band with the free hand. Alternatively, eccentric training may be carried out with a pulley system as performed by Jonsson et al in a previous study.

**DISCUSSION**

RC pathology may generate from a series of problems, for example: acute/chronic inflammation, fibrosis, degenerative changes, impingement syndrome, partial or full-thickness RC tears. This makes it difficult for clinicians to differentiate between the involved structures, with some researchers questioning the validity of patho-anatomical classifications. Some authors have instead demonstrated better outcomes when classifications are not made upon anatomy, but on mechanical presentation.

The MDT® assessment and classification system has been successfully utilized with good reliability in the spine and over a series of peripheral joints and structures, with promising results when applied at the glenohumeral joint. In a survey conducted by May and Rosendale among therapists with a MDT® diploma (the highest level of training), 100% of the cases were classified according to the MDT® method, with about two thirds of the cases falling into one of the three major subgroups (derangement, dysfunction and contractile

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**Figure 2.** Concentric contraction with weight. A) Initial position, B) Final position
syndromes). MDT® assessment may help differentiate the origin of pain, for example: spinal or peripheral, and may help alert clinicians to non-mechanical conditions as in cases of malignancy.

Therapeutic exercise and its progression is key in the MDT® method. Mechanical loading is in fact essential for tendon homeostasis, preventing negative effects of immobilization, and helping collagen turnover of the tendon. Treatments generally follow a progression from isometric training to eccentric training in the later stages. Since concentric training offers less tension than eccentric training, it is more suitable in the initial stages, while eccentric training is generally prescribed in the later stages as it is thought to be more demanding. Eccentric training has become more and more popular over the last years on tendinopathies due to research with good clinical outcomes, including research on shoulder disorders. Eccentric training is proposed to drive the tendon biological response by remodeling internal architecture through the process of mechanotransduction.

Although the MDT® method has an impact on signs and symptoms, it is also important to remember that RC pathology is probably due to several factors. Therefore, combinations with other rehabilitative interventions may be beneficial when dealing with people with RC tendinopathies. As inflammation does not seem to have a primary role in tendinopathies, the use of anti-inflammatory drugs is discouraged as they may have negative effects on tendon healing. Alteration of shoulder muscle ratios, shoulder dyskinesis, and posterior capsule tightness have been recognized as modifiable contributors to the development of RC tendinopathies, may be addressed with specific muscle strengthening, and capsule stretching. Therapeutic modalities may be included as they may help the healing process, however, the evidence on modality use with shoulder tendinopathies is limited and often contradictory.

The MDT® method may not always be well accepted by patients in cases of shoulder contractile dysfunction. Pain that occurs during performance of therapeutic exercise when treating contractile dysfunctions may alert and prevent patients from continuing the exercise. However, pain that easily subsides may facilitate remodeling of RC dysfunctional tissues. Moreover, MDT® principles of progressions appear to be safe also in cases of diagnosed partial RC tears as already documented in two previous studies.

Contractile dysfunction syndrome requires time and rigorous adherence to the exercise program in order to improve symptoms. Adherence to self-management...
exercises may be improved with supervised exercise therapy and when care providers' style, and content of exercise programs are positively experienced. Finally, although contractile dysfunction shows typical features and it is relatively simple to recognize, its management according to MDT® method should be mastered by clinicians with at least a minimal knowledge of the method (The McKenzie Institute®).

CONCLUSIONS
Due to the high prevalence of RC tendinopathy among the general and the sportive populations, the MDT® method may offer an inexpensive, and an effective solution to consider when treating musculoskeletal issue. However, more research is warranted especially on shoulder disorders.

REFERENCES


ABSTRACT

One of the main priorities of rehabilitation after anterior cruciate ligament reconstruction (ACLR) surgery is the restoration of knee extensor muscle strength. Residual deficits in knee extensor muscle size and strength after injury are linked to poor biomechanics, reduced knee function, increased knee osteoarthritis risk, as well as heightened risk of re-injury upon return to sport. Most studies indicate that knee extensor muscle strength is typically not resolved prior to return to sport. This clinical commentary discusses strategies to optimize and accelerate the recovery of knee extensor strength post-surgery, with the purpose to support the clinician with evidence-based strategies to implement into clinical practice. Principally, two strategies exist to normalize quadriceps strength after surgery, 1) limiting strength loss after injury and surgery and 2) maximizing and accelerating the recovery of strength after surgery. Optimal preparation for surgery and a focused attempt to resolve arthrogenic muscle inhibition are essential in the pre and post-operative period prior to the inclusion of a periodized strength training program. Often voluntary strengthening alone is insufficient to fully restore knee extensor muscle strength and the use of electrical stimulation and where necessary the use of blood flow restriction training with low loads can support strength recovery, particularly in patients who are significantly load compromised and experience pain during exercise. Resistance training should employ all contraction modes, utilize open and closed kinetic chain exercise of both limbs, and progress from isolated to functional strength training, as part of a periodized approach to restoring neuromuscular function. Furthermore, thinking beyond the knee musculature and correcting core and hip dysfunction is also important to ensure an optimal knee extension strengthening program. The purpose of this clinical commentary is to provide a series of evidenced based strategies which can be implemented by clinicians responsible for the rehabilitation of patients after ACLR.

Level of evidence: 5

Key words: Anterior cruciate ligament reconstruction, functional recovery, injury prevention, rehabilitation, sports medicine
INTRODUCTION
One of the main priorities of rehabilitation after anterior cruciate ligament reconstruction (ACLR) surgery is the restoration of knee extensor muscle strength. After ACL injury and subsequent surgery, there is often considerable pain, swelling/inflammation, reduced function, muscle atrophy and strength loss. Residual deficits in knee extensor muscle size and strength after injury are linked to poor biomechanics, reduced knee function and increased knee osteoarthritis risk, poorer outcomes and heightened risk of re-injury upon RTS. For example, those who reported a limb symmetry index (LSI) less than 90% were at nearly three times greater risk of sustaining a subsequent knee injury than who achieved more than 90% LSI (33 vs 12%). For every 1%-point increase in quadriceps symmetry there was a 3% reduction in re-injury rate. Early return to sport (RTS), without sufficient neuromuscular recovery is associated with early knee osteoarthritis changes only one year after surgery.

Most researchers have indicated that knee extensor muscle strength is typically not achieved by six-months after surgery or at the time of return to play. Furthermore, recent research suggests that the conventional LSI may underestimate the deficits in knee extensor muscle strength post-surgery. Only 29% of patients achieved a LSI less than 10% when the reconstructed limb was compared to pre-injury injured limb values at six-months post ACLR surgery, compared to 57% who achieved this marker when using the conventional LSI (when injured limb is compared to contralateral limb). As such deficits in knee extensor strength are possibly even more marked than previously thought, with only one in three to one in four achieving this marker prior to medical discharge and RTS. Importantly, the restoration of knee extensor muscle strength represents a mid-stage rehabilitation marker, one which should be achieved prior to restoring movement quality, functional strength, power and explosive muscle strength as well as subsequent sport-specific re-training and RTS. Therefore, the inability to restore knee extensor muscle strength in a timely fashion is likely resulting in incomplete recovery in other important rehabilitation factors (e.g., explosive strength and motor patterning). In order to achieve complete functional recovery and optimise the late-stage rehabilitation process, there is a need to first optimize and accelerate the recovery of knee extensor muscle strength to i) provide an optimal platform on which late-stage rehabilitation can commence and ii) actually allow time in most clinical cases for late-stage rehabilitation and an appropriate RTS process.

The aim of this clinical commentary/narrative review is to discuss strategies to optimize and accelerate the recovery of quadriceps strength post ACLR surgery. This will provide practitioners working with individuals after with important theoretical and practical information which can be applied to their functional recovery framework to help optimise their patient outcomes.

WHAT ARE THE REASONS FOR QUADRICEPS WEAKNESS AFTER ACLR?
Determining the reasons for quadriceps weakness after ACLR are essential to design strategies to optimize patient functional recovery. Typically, there is limited consideration of the notion that if one fails to overcome muscle inhibition one will be unable to optimally restore muscle mass and strength. Arthrogenic muscle inhibition (AMI) is hypothesized to be present after ACLR and contribute to the ever-present post-traumatic knee extensor muscle strength deficit. Loss of mechanoreceptors from the ACL is thought to disrupt the ligamentous–muscular reflex between the ACL and the quadriceps, leading to an inability to actively recruit high-threshold motor units during voluntary quadriceps contractions. Furthermore, pain and swelling both result in neuromuscular inhibition via the AMI process and resultant muscle atrophy and weakness. AMI typically limits the ability to achieve desired intensity levels and neuromuscular activation, and is often present bilaterally following unilateral ACLR, and in some cases, can be equivalent to the injured limb.

Muscle strength is influenced by both neural and morphological factors. The loss of function and significant neural inhibition can result in marked muscle atrophy which contribute to loss of strength and function. Williams et al. reported that quadriceps atrophy and activation failure together account for approximately 62% of the variance in the quadriceps weakness of ACL-deficient non-copers, suggesting
atrophy also plays a significant role in reducing quadriceps strength. As such, the resolution of muscle mass and neural activation are key aspects of ACL rehabilitation and strategies to restore them are of considerable importance.

**MAXIMIZING KNEE EXTENSOR STRENGTH RECOVERY AFTER ACL SURGERY**

Two strategies exist to normalize quadriceps strength after surgery. These include:

1. Limit strength loss after injury and surgery and
2. Maximize and accelerate the recovery of strength after surgery.

**STRATEGIES TO LIMIT STRENGTH LOSS AFTER ACL RECONSTRUCTION**

The greater the degree of muscle atrophy and larger strength deficits post-surgery the longer time it will take to restore these deficits. In terms of this approach there are two strategies to consider a) the level of atrophy and strength loss prior to surgery and b) the degree of atrophy and strength loss post-surgery.

**Optimally prepare for surgery**

Optimally preparing for surgery and resolving deficits in muscle mass and strength would be expected to enhance post-operative function. The research available indicates that prehabilitation (a five to six-week program focusing on restoration of muscle strength, quadriceps hypertrophy and hop performance) results in superior knee function post-operatively.\(^\text{18-20}\) Recent research shows that patients with better pre-operative quadriceps activation demonstrated greater post-operative activation, whilst patients with better pre-operative strength also demonstrated better post-operative strength.\(^\text{21}\) There is no consensus on the optimal level of pre-surgery function.\(^\text{22}\) Grindem et al.\(^\text{18}\) recommended patients should have a LSI of 90% for muscle strength and hop performance prior to ACL reconstruction, which may not be plausible for all patients.

**Resolve Arthrogenic Muscle Inhibition (AMI) quickly post-surgery**

After injury or surgery, there is often considerable pain and swelling/inflammation. Acute injury management should adhere to the principles of POLICE, (protection, optimal loading, ice, compression and elevation)\(^\text{23}\) to ensure joint protection and healing, removal of pain and swelling but maintenance and gradual restoration of function through optimal load application. Pain and swelling both result in neuromuscular inhibition via the AMI process and resultant muscle atrophy and weakness.\(^\text{8,15}\) The clinician should utilize a variety of interventions to combat pain, swelling and AMI to be able to progress through the remainder of the rehabilitation program optimally.

**a) Use Anaesthetics.** Local anaesthetics may reverse AMI through the reduction of pain and may also reduce AMI by blocking other afferents contributing to the inhibition. AMI persists once pain has subsided and can be induced in the absence of pain (e.g., the effusion model does not cause pain but results in AMI),\(^\text{24}\) therefore, rehabilitation strategies effective in removing AMI, should not be focused solely on removing painful stimuli.

**b) Use Ice.** Use of cryotherapy (ice), compression and elevation are standard practices as part of acute injury management, in line with the POLICE\(^\text{23}\) recommendations. Cooling of the knee joint may also serve to decrease AMI\(^\text{24}\) and facilitate increased quadriceps activation. The effects are thought to be maintained after the removal of cryotherapy and as such, may serve as a strategy to temporarily reduce AMI and increase quadriceps recruitment prior to exercise.

**c) Utilize transcutaneous electrical nerve stimulation.** Transcutaneous electrical nerve stimulation (TENS) of the cutaneous nerves has been shown to reduce presynaptic inhibition,\(^\text{25}\) which is a contributor to AMI.\(^\text{26}\) Hopkins et al.\(^\text{24}\) demonstrated that 30 mins of TENS treatment reversed the inhibitory effects of induced knee effusion. However, this was temporary as the inhibition returned to baseline levels after the machine was turned off. As such, the greatest effect of TENS appears as a supplement to active exercise with an effect to minimize AMI and promote quadriceps recruitment.\(^\text{15,27}\)
Optimal load to preserve quadriceps strength
Optimal loading may be defined as the load applied to structures that maximizes physiological adaptation.\textsuperscript{28} Additionally, in the context after injury, it can also be considered as the load which ‘minimizes adaptation’ (e.g., muscle strength loss and atrophy due to functional limitations).

Achieving optimal loading is challenging. It is essential that in the early periods after surgery, the rehabilitation program incorporates progressive optimal loading to prevent muscle atrophy and strength loss and subsequently facilitate functional recovery. Use of electrical stimulation can support strength preservation, through providing a stimulus to activate the motor units, which may be inhibited due to AMI. The use of electrical stimulation and voluntary isometric contractions can support muscle mass and strength preservation in the early phase.\textsuperscript{29} Monitoring pain and joint effusion particularly during the early phases of rehabilitation are important to ensure that the applied training stimulus is not excessive and causing tissue overload. Measurement of pain via the use of the visual analog scale should be taken regularly and recorded. Swelling can be measured with limb girth daily. Measurement of knee circumference at the patella has been shown to have strong intra-tester reliability and good sensitivity to change.\textsuperscript{30} Within, the knee, change greater than one centimeter was shown to be clinically significant.

STRATEGIES TO MAXIMISE AND ACCELERATE THE RECOVERY OF STRENGTH AFTER ACLR

Incorporate a periodized strength training program
Following the satisfactory resolution of pain, swelling and AMI, it is important to incorporate a periodized strength training program to fully restore neuromuscular function of the knee extensors, as well as other muscles. Restoration of quadriceps function requires the application of strength and conditioning principles applied to the injured athlete,\textsuperscript{31} and can be considered as optimal re-conditioning. Key strategies after ACLR are to restore muscle mass, strength (across the force-velocity curve), explosive strength (rate of force development), power and coordination (e.g., ability to use this strength in sport-specific movements). A significant challenge for rehabilitation specialists is designing optimal training programmes that facilitate neural and musculotendon adaptations whilst been mindful of biological healing constraints, and safety.\textsuperscript{32,33} To fully restore neuromuscular performance after ACLR it is important to incorporate a periodized neuromuscular training program, respecting tissue healing times and the patients individualised functional recovery.

Periodization can be defined as the planned manipulation of training variables (load, sets and repetition) in order to maximize training adaptations and prevent over-training.\textsuperscript{31} There is a lack of evidence concerning the best periodization approach after ACLR, but it is the authors view and that of others\textsuperscript{31} that the use of periodization in rehabilitation is superior to non-periodized approaches and the use of non-linear approaches, respecting the phases of rehabilitation is important. When designing the program, it is important to have an understanding of how training variables can manipulate training outcome. This entails understanding how changes in load/ intensity, volume and set configurations can influence strength adaptations (and their associated mechanism) after ACLR, placed alongside the functional recovery process.

Important considerations in terms of resistance training are i) the mechanical tension on the muscle; ii) the metabolic stress induced through training and iii) the extent of muscle damage. Mechanical tension refers to the loading of muscle and is proposed to disrupt skeletal muscle structures, compromising the integrity of individual muscle fibres and leading to cellular responses via stimulation of the mTOR pathway.\textsuperscript{34} Local metabolic stress involves the accumulation of metabolic by-products such as hydrogen ions, and blood lactate from fast glycolysis,\textsuperscript{35,36} which then stimulate catabolism; while muscle damage is proposed to lead to hypertrophic responses secondary to muscle damage, subsequent inflammation and upregulation of muscle synthesis to repair the tissue. The manipulation of various resistance training variables can influence muscle strength and size and include training volume, loading of exercise intensity, training frequency, training to failure, exercise variation, contraction type and recovery between efforts. Considering these
training variables are important when designing an optimal resistance training program for ACL patients to RTS quickly and optimally.

In general, it appears that high volume resistance training is necessary to bring about increased strength and muscle size. Schoenfeld et al. concluded that high volume resistance training produces greater gains in muscle mass than low volume training. It is thought that high volume training may enhance muscle mass gains due to prolonged metabolic stress. There is a balance however, between a high training volume and an excessive volume which may lead to over-training and potential joint stress and tissue overload. Amirthalingam et al. found no significant difference in muscle hypertrophy when training with 5 sets of 10 repetition versus 10 sets of 10 repetitions over six weeks of training. As such, it is thought that volume and muscle adaptation are not linearly related but instead follows an inverted ‘U’ shape with an optimal training volume to elicit muscle hypertrophy and strength. This exact value is not known and may relate to the individual, the training history, recruitment, recovery strategies as well as lifestyle outside of the clinic (e.g., sufficient recovery practices, sleep, nutrition and rest etc.), and possible unresolved biological consequences of injury (e.g., pain, swelling and AMI).

It is thought that the mechanical tension or load, typically presented as a percentage of maximal load that can be lifted (one repetition maximum, 1RM) is important for maximising muscle hypertrophy and strength. This is because the increased load results in increased mechanical tension on the muscle which is an important stimulus. The American College of Sports Medicine (ACSM) recommends loads of 60-70% 1RM for the development of muscle strength and 70-85% for hypertrophy. Traditionally, it was thought that very high loads were necessary to bring about activation of all type II motor units based on the Henneman size principle and achieve full and complete muscle hypertrophy (targeted at all motor units). However, it is suggested that more low-load training also recruits fast-twitch muscle fibres, provided the working set is continued close to volitional fatigue. There appears to be no difference or at most a small trend for higher muscle hypertrophy with higher load resistance training compared to low-load training in terms of muscle hypertrophy. Training set intensity however, can have marked effects on other variables such as maximal eccentric strength and rate of force development (RFD). For example, conventional resistance training using loads of 70% maximal has been shown to enhance maximal muscle strength and muscle hypertrophy but results in a reduction in the relative RFD (scaled to maximal voluntary force) and as such no change in RFD. The importance for RFD in the rehabilitation program has recently been discussed, and it is apparent that following full and complete restoration of muscle strength after ACLR, there are still significant 30% deficits in RFD. RFD was only restored following a subsequent period of power training 12 months after surgery. Recently, Mangine et al. showed that moderate intensity resistance training with loads at 70% 1RM over eight weeks resulted in no change in RFD, whereas strength training using high loads (90% maximal) elicited large increases in RFD (+70%). As such, each training intensity may bring about specific underlying adaptations and evoke differing alterations in mechanical variables (strength, power, RFD). Obviously, high load strength training (>85-90% 1RM) can only be implemented following satisfactory recovery of range of motion, pain and swelling, AMI and sufficient muscle mass to tolerate these high forces.

It is recommended to utilize a periodized resistance training program throughout the ACL rehabilitation program, beginning with optimal post-operative recovery, prior to moderate to high volume low to moderate loads resistance training until failure to promote initial strength gains and hypertrophy of all motor units (achieved largely through metabolic stimuli), when the joint is more load compromised and cannot likely tolerate high forces; followed by a period of moderate to high intensity (70-80% 1RM) resistance training with moderate to high volume (5-8 sets) with the goal to fully restore muscle size and maximise strength; finishing with very high intensity strength training (90%, / 5RM) and lower volumes in the latter phases of rehabilitation to target maximal voluntary activation, eccentric maximal muscle strength and restore power and explosive strength (Figure 1). Obviously, it is important to respect tissue healing, joint response and individual
adaptations, and produce a minimum stimulus in the post-operative recovery period to preserve muscle mass, but not overload the joint.

**Open chain or closed chain, isolated or functional?**

There is no consensus among the existing published evidence as to whether closed kinetic chain (CKC) or open kinetic chain (OKC) exercises should be the intervention of choice following ACLR. There are doubts about safety of OKC exercises, which are arguably unsupported by substantial published evidence. OKC exercises can be useful as they isolate the muscle and limit the involvement of other muscle groups and thus, can ensure higher and more complete activation and fatigue of the target muscle. Some studies have shown that OKC exercises or OKC plus CKC exercises are more effective than CKC exercises alone in improving quadriceps strength after ACL reconstruction and in patients who are ACL deficient. Others have found no differences in patients' quadriceps strength when comparing the two types of exercises. Available clinical research suggests that cautiously incorporating OKC exercises into ACL rehabilitation will improve quadriceps function and the authors advocate the use of both OKC and CKC exercise.

A particular consideration with knee extensor strengthening after ACLR, is minimizing patellofemoral joint (PFJ) stress, given the high prevalence of patients who go on to develop patellofemoral pain syndrome (PFPS) after ACLR surgery. In OKC exercises such as knee extensions, quadriceps muscle force and PFJ stress are greatest near full extension. Conversely, in CKC exercises such as lunges and the leg press, quadriceps muscle force and PFJ stress are highest near full flexion. As such, it is recommended to initially restrict high load OKC strengthening between 40-90 degrees of knee flexion, and CKC between 0-80 degrees, which collectively can enable complete strengthening through the arc of motion, at reduced PFJ stress. Each can be implemented at a similar time (typically 4 weeks after surgery, but with an initial focus on control as opposed to load), respecting the principles of optimal load progressions.

When there are residual deficits in knee extensor strength (typical after ACLR surgery), it is essential to implement isolated strength techniques as opposed to functional exercises such as squat with load. This is because, significant strength deficits result in biomechanical compensatory strategies i.e., cheating where the hip extensors are utilised instead of the knee extensors. Therefore, functional exercises alone are an inadequate means for resolving quadriceps weakness and restoring normal quadriceps strength. As isolated quadriceps strength increases, a gradual increase in the use of functional strength training techniques such as squat, deadlift, lunge and their derivatives can be implemented.

Functional strength refers to the ability to produce force in movements in which the muscles are typically used and is essential for athletic performance. Functional strength is also important for optimal movement quality and force dissipation. For example, landing from a jump results in 1.5-2 times body mass transferred through each limb.
An inability of the neuromuscular system to tolerate these forces, i.e. low functional eccentric strength of the kinetic chain would result in these forces being either off-loaded from the sagittal plane to the frontal plane and/or absorbed via the ligaments, tendon and joints, thus potentially lead to joint or tendon overload.68-69 As such, it is essential to have both a sufficient knee extension strength and global functional strength capacity to ensure that the neuromuscular system can adequately generate and ‘accept’ high ground reaction forces during sporting type movements.

The authors suggest that isolated machine based strengthening techniques be the main strategy to restore knee extensor strength in the early to middle phases of rehabilitation (e.g., week 4 to week 12 after surgery as an example) and once the patient has resolved at least 80% of the knee extensors strength of their contralateral limb70 (assessed through isokinetic testing of the knee extensors, typically at 90-120 days post-surgery in our patients). In general, it is advised to initially implement isolated OKC and CKC early in the rehabilitation period, using initially isometric contractions (with additional modalities, see subsequent text), with specific joint angle restrictions to limit PFJ stress. Motor patterning and muscle imbalance correctives at adjacent joints should accompany this work to prepare for functional strengthening. Once the patient has restored knee extensors strength to within 20% of the contralateral side, moderate to high load strength training using both isolated (high load, 5RM) and functional (moderate load, 8RM) techniques can be used.

**Target the VMO?**

PFP is common following ACLR with 30-50% still experiencing PFP at 1 year after surgery,55-57 and is problematic for the recovery of quadriceps strength after ACLR as it will result in PF inhibition, and limit quadriceps activation. Often practitioners work around patients PFP and lower the loads to a point of no pain (as pain is a potent inhibitor and contributor to AMI), but this often results in a load which is insufficient to elicit sufficient stimulus for muscle hypertrophy and strength adaptation. The resolution of PFP is essential to full and complete knee extensor strength recovery. There is a lack of consensus on the source of pain in relation to PFP.71 However, patellar maltracking including increased lateral patellar translation,72-74 tilt72 and spin,74 as well as increased lateral PFJ stress75,76 may associate with PFPS. As the vastus medialis oblique (VMO) has the ability to control lateral patellar tracking, delay or weakness of VMO is considered a key biomechanical risk factor for patellar maltracking.77 As such, rehabilitation specialists and researchers often advocate selective strengthening on the VMO, to help restore normal patellofemoral biomechanics and reduce pain, thus supporting more optimal quadriceps recovery. There is however, debate, as to whether it is possible to selectively strengthen the VMO, with current evidence suggesting that voluntary strengthening techniques will not specifically recruit the VMO.78-81 In those with patella maltracking, the use of electromyography (EMG) biofeedback measures during neuromuscular contractions can provide auditory or visual feedback signals, designed to increase Awareness and voluntary control of muscle activation. When utilized in conjunction with strength training, EMG biofeedback aimed at increasing VMO activation while maintaining constant vastus lateralis (VL) activity has been shown to improve VMO/VL activation ratios.82 Additionally, taping of the patella may be an effective strategy to transiently optimise patella tracking. Using taping techniques to control patella tracking during resistance exercise have found increased patient tolerance to knee joint loading, increased VMO activity, and improved onset of the VMO in relation to the VL muscles.83-86

**Think beyond the knee**

Typically, early and mid-phase programs focus exclusively on resolving knee mechanics. It is becoming accepted that weakness of core and hip muscles are risk factors in lower extremity injury risk87-90 and in particular ACL injuries.91,92 A systematic review by Petersen et al.93 revealed deficits in hip muscle strength after ACLR. Beyond injury prevention, proximal dysfunction is associated with high risk movement biomechanics and linked to PFP.87,90 Strong evidence currently exists that patients with anterior knee pain have deficits in hip abduction, hip extension and external rotation strength.94 Hip muscle strengthening is effective in reducing the
Utilize the powers of electrical stimulation

Neuromuscular electrical stimulation (NMES) appears to be a promising intervention for use after ACLR. NMES allows for the direct activation of the motor axon, and could allow for the direct recruitment of the inhibited motoneurons. Muscle activation by means of NMES allows for the recruitment of a greater proportion of type II muscle fibers when compared with voluntary contractions of a similar intensity.96-98 Furthermore, although, during voluntary contractions there is a logical order of recruitment beginning with the smallest motor units and progressing to the largest motor units,42 NMES results in a reversal of the order of motor unit recruitment.99 The activation of type II motor units are essential to achieve a higher level of quadriceps force production, as well as sufficient power and RFD. As such, their recruitment by means of NMES undoubtedly should aid in the quest to achieve complete recovery of quadriceps strength. A recent meta-analysis reported that use of NMES in addition to standard physical therapy appears to significantly improve quadriceps strength and physical function in the early post-operative period compared to standard physical therapy alone.29

Incorporate blood flow restriction training in selective patients

In the load compromised patient (early after surgery) or in those patients who experience PFP and subsequent quadriceps inhibition and as such, cannot achieve the required load and activation to bring about the necessary stimulus for adaptation, blood flow restriction (BFR) training may be an effective therapy. Low-intensity resistance training with BFR can result in in greater strength and muscle hypertrophy when compared to resistance training with the same intensity under normal flow100-103 and comparable to gains with moderate to high intensity resistance training.104 Under ischemic conditioning, fast twitch fibres are recruited even under low intensity activity, as type I motor units fatigue rapidly which allows for the recruitment of type II units earlier. BFR training may also serve as an effective stimulus during an unloading phase for patients because it results in a positive training adaptation, although causing little to no muscle damage105 and thus, can be used sparingly throughout the rehabilitation cycle. Low-load BFR was shown to be superior at improving functional capacity and pain in patients with PFP compared to moderate intensity resistance training with BFR.104 Sub-group analysis revealed that in those with pain on resisted knee extension there was considerable benefits in enhancing function, but is similar to resistance training at moderate to high loads (70% 1RM) in those without pain on resisted knee extension.104 As such, BFR therapy at low loads can may be a useful tool to develop muscle strength in patients who are unable to perform high-resistance exercise or patients who have persistent extremity weakness despite traditional therapy, or maybe used sparingly as part of a periodized strength training program.

Don't forget the other leg

An ACL injury has recently been suggested as a single leg injury, but a double leg problem.105 Deficits in knee extensor strength, neuromuscular control and proprioception, which are prevalent in the injured limb are also present in the contralateral uninjured limb.106-108 As discussed, this lower than optimal level of strength in the contralateral limb can result in an overestimation of knee extensor strength of the injured when examining the limb symmetry index in the conventional manner (injured versus uninjured).8 As such, it is advised to ensure that rehabilitation target both limbs. Additionally, cross-education training, which is the increase in muscle force on the untrained side after resistance training of the contralateral homologous limb muscle,109 has been suggested to accelerate the recovery of the injured limbs strength after ACLR and augment the LSI,110 although this is not a consistent finding.111

SUMMARY AND IMPLEMENTATION

The restoration of knee extensor muscle size, activation and strength forms essential components of rehabilitation after ACLR. AMI can limit the desired activation values during resistance training and limit strength recovery after surgery. It is recommended that optimal preparation for surgery, the
Table 1. A schematic layout of an example periodized resistance training approach for the athlete after anterior cruciate ligament reconstruction. The program involves one pre-operative and five post-operative stages aligned with the functional recovery status of the athlete after surgery. The particular goal, strategy and approach are outlined discussing the factor relevant within the text. The program is a typical approach (and allocated time) to a professional athlete, who was able to return to team training at six months after reconstructive surgery. Time lines are dependent upon the injury (e.g., concomitant injury, such as cartilage, medial collateral ligament), and individual healing and progression time lines. Criteria and not time should be used to transition between stages.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Weeks</th>
<th>Goal</th>
<th>Strategy</th>
<th>Knee extension exercises</th>
<th>Supplementary modalities (injured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6 weeks pre-op to surgery</td>
<td>Optimally prepare for surgery - Resistance training to restore muscle mass and strength to within 90% of contralateral limb</td>
<td>POLICE - Resistance training (isolated, OKC, CKC, functional) depending upon post-injury status, low intensity (plus BFRT), moderate intensity (isolated and functional plus electrical stimulation) to high load training</td>
<td>OKC – Knee extension - CKC – Leg press - Functional: squat &amp; deadlift and derivatives, BL and UL - Plyometrics (when good function)</td>
<td>Electrical stimulation - BFRT during isolated strength tasks with optimal supervision</td>
</tr>
<tr>
<td>1</td>
<td>0-4</td>
<td>Recover from surgery - Resolve pain, swelling, AMI - Prevent atrophy and strength deficits of injured limb - Preserve function of uninjured limb</td>
<td>Injury treatment - POLICE - High load, low volume resistance training of uninjured limb - Low load isometrics with electrical stimulation for injured limb</td>
<td>Injured limb – Isometric isolated only plus electrical stimulation - Un-injured limb – same exercise, maximal intensity</td>
<td>Electrical stimulation - ICE - TENS - Massage - Cross-education</td>
</tr>
<tr>
<td>2</td>
<td>5-8</td>
<td>Muscle endurance (and hypertrophy)</td>
<td>Low to moderate load isolated resistance training with additional modalities to support muscle endurance and strength recovery, 12-20 RM</td>
<td>Low load knee control (ensure optimal patellar tracking and VMO recruitment) - OKC and CKC - High load low volume RT for un-injured leg</td>
<td>Electrical stimulation - Cross-education - Optimal preparation to reduce AMI – cryotherapy, massage, stretching, pre-activation, TENS - Non-load bearing lumbo-pelvic exercises to re-activate local core stability system</td>
</tr>
<tr>
<td>3</td>
<td>9-12</td>
<td>Muscle hypertrophy and knee extensor strength recovery to within 20% of contralateral limb</td>
<td>Moderate to high volume of low and moderate intensity RT (6-10 sets of 8-12 RM) across at least 2 exercises (OCK and CKC)</td>
<td>Low load (plus BFRT) and moderate load RT Example, 3 sets of knee extensions and 4 sets leg press with either BFRT or electrical stimulation</td>
<td>Electrical stimulation - BFRT - Cross-education - Weight-bearing and non weight-bearing lumbo-pelvic control and strengthening exercises</td>
</tr>
<tr>
<td>4</td>
<td>13-18</td>
<td>Maximise muscle strength to within 10% of ‘trained’ contralateral limb - Develop CKC maximal strength (iso, ecc, con) - Develop functional strength - Develop landing / deceleration control</td>
<td>Moderate to heavy load isolated RT (OKC and CKC, 5-10 RM) of moderate volume - Functional RT (6-12 RM) - Motor pattern training - Bilateral landing drills/ running initiation</td>
<td>Squat and derivatives - Deadlift and derivatives - UL and BL - Isolated – Knee extension, leg press - On-field running and deceleration drills</td>
<td>Optimal preparation (warm up, massage, stretching, pre-activation) - Optimal technique in functional exercises - Biofeedback in movement training - Core stability training</td>
</tr>
<tr>
<td>5</td>
<td>19-24+</td>
<td>Restore/ develop explosive neuromuscular performance</td>
<td>High intensity, low volume neuromuscular conditioning - Heavy load functional RT (3-8RM) - Power training - Agility exercises on-field</td>
<td>Functional RT - Plyometrics - Ballistics - Olympic lifts - OFR</td>
<td>Optimal warm up and training prescription</td>
</tr>
</tbody>
</table>

AMI= artrogenic muscle inhibition; CKC= closed kinetic chain; OKC= open kinetic chain; iso= isometric; ecc= eccentric; con= concentric; BFRT= blood flow restriction training; POLICE= protection, optimal loading, ice, compression and elevation; RM= repetition maximum; BL= bilateral; UL= unilateral; OFR= on-field rehabilitation; TENS= transcutaneous electrical stimulation
adoption of POLICE and focused attempt to resolve AMI are essential in the pre and post-operative period prior to the inclusion of a periodised strength training program. Appreciation of strength and conditioning principles including load, volume, rest and recovery (between sets and sessions) are important. Often voluntary strengthening alone is insufficient to fully restore knee extensor muscle strength and the use of electrical stimulation and where necessary the use of BFR training with low loads can support strength recovery, particularly in patients who are significantly load compromised and experience pain during exercise. Resistance training should employ all contraction modes, utilise OKC and CKC exercise, begin with isolated strength tasks and finish and progress to functional strength training and agility type exercises to prepare for sporting practice. Restoring balance between the quadricep muscles and resolving possible patellar tracking issues, through manual therapy, biofeedback training and stretching are important additional considerations. Finally, thinking beyond the knee and correcting core and hip dysfunction may be important to ensure an optimal knee extension strengthening program. Optimizing the use of disinhibitory techniques (e.g., ICE, massage) and activation techniques (pre-activation exercises, electrical stimulation, TENS) may support more optimised training outcomes. It is hoped that these recommendations may support practitioners who have the responsibility to rehabilitate patients after ACLR, and support the quest to enhance patient outcomes (RTS rates, long term knee joint health and re-injury risk) after ACLR surgery.

REFERENCES


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