IJSPT

EDITORIAL STAFF

Michael L. Voight, PT, DHSc, OCS, SCS, ATC
Editor-in-Chief

Barbara Hoogenboom, PT, EdD, SCS, ATC
Grand Valley State University
Grand Rapids, Michigan - USA

Senior Associate Editor

Robert Manske, PT, DPT, Med, SCS, ATC, CSCS
Wichita State University
Wichita, Kansas – USA

Associate Editor, Thematic Issues

Phil Page, PT, PhD, ATC, CSCS
Performance Health
Baton Rouge, Louisiana—USA

Associate Review Editor

John Dewitt PT, DPT, SCS, ATC
The Ohio State University Sports Medicine
Columbus, Ohio - USA

Terry Grindstaff PhD, PT, ATC
Creighton University
Omaha, Nebraska - USA

International Associate Editors

Colin Paterson,
University of Brighton
Brighton, England –United Kingdom

Anthony G. Schneiders, PT, PhD
Central Queensland University
Bundaberg, Queensland – Australia

Kristian Thorborg, PT, PhD
Copenhagen University Hospital Hvidovre
Hvidovre—Denmark

Ashley Campbell
Associate Editor, Manuscript Coordinator

Mary Wilkinson
Managing Editor

ADVERTISING SALES

The International Journal of Sports Physical Therapy accepts advertising. Email Mary Wilkinson, Marketing Director, at mwwilkinson@spts.org or contact by phone at 317.501.0805.

IJSPT is a bimonthly publication, with release dates in February, April, June, August, October and December. It is published by the Sports Physical Therapy Section.

ISSN 2159-2896

IJSPT

INTERNATIONAL JOURNAL OF SPORTS PHYSICAL THERAPY

EXECUTIVE COMMITTEE

Walter L. Jenkins, PT, DHS, LATC, ATC
President

Blaise Williams, PT, PhD
Vice President

Mitchell Rauh, PT, PhD, MPH, FACSM
Secretary

Bryan Heiderscheit, PT, PhD
Treasurer

Stacey J. Pagorek, PT, DPT, SCS, ATC
Representative-At-Large

ADMINISTRATION

Mark S. De Carlo, PT, DPT, MHA, SCS, ATC
Executive Director

Mary Wilkinson
Director of Marketing/Webmaster
Managing Editor, Publications

CONTACT INFORMATION

P.O. Box 431
Zionsville, Indiana 46077
877.732.5009 Toll Free
317.669.8276 Fax
www.spts.org

IJSPT is an official journal of the International Federation of Sports Physical Therapy (IFSP).
TABLE OF CONTENTS
VOLUME 13, NUMBER 4

SYSTEMATIC REVIEW – META ANALYSIS

561 Multi-Joint Influence of Patient Demographics and Graft Types on ACL Second Injury Rates in Ipsilateral Versus Contralateral Knees: A Systematic Review and Meta-Analysis.
Authors: Naousreh Z, Adams G, Przybylowski O, Logerstedt D

575 Risk Factors Associated with Non-Contact Anterior Cruciate Ligament Injury: A Systematic Review.
Authors: Pfeifer CE, Beattie PF, Sacko RS, Hand A

ORIGINAL RESEARCH

588 Modifying Stance Alters the Peak Knee Adduction Moment During a Golf Swing.
Authors: Hooker QL, Shapiro R, Malone T, Pohl MB

Authors: Terry AC, Thelen MD, Crowell M, Goss DL

605 Injury Identification: The Efficacy of the Functional Movement Screen™ in Female and Male Rugby Union Players.
Authors: Armstrong R, Greg M

Authors: Cornell DJ, Ebersole KT

633 Altering Cadence or Vertical Oscillation During Running: Effects on Running Related Injury Factors.
Authors: Adams D, Pozzi F, Willy R, Carrol A, Zien J

643 Leg-length Inequality and Running-Related Injury Among High School Runners.
Authors: Rauh M

652 The Effects of an Acute Bout of Foam Rolling on Hip Range of Motion on Different Tissues.
Authors: Hall M, Smith JC

661 No Effect of Kinesiology Tape on Passive Tension, Strength or Quadriceps Muscle Activation of During Maximal Voluntary Isometric Contractions In Resistance Trained Men.
Authors: deFreitas FS, Brown LE, Gomes WA, Behm DG, Marchetti PH

Authors: Bishop BN, Greenstein J, Etnoyer-Slaski JL, Sterling H, Topp R

676 Relative Joint Contribution to Joint Hypermobility in Rugby Players, Netballers and Dancers: The Need For Careful Consideration of Lumbar Flexion.
Authors: Armstrong R

687 Scapular Substitution after Rotator Cuff Repair Correlates with Postoperative Patient Outcome.
Authors: Baumgarten KM, Osborn R, Schwanele WE, Zens MJ, Helgesper EA

700 Biomechanical Influences of a Postural Compression Garment on Scapular Positioning.
Authors: Gascon SS, Gilmer GG, Hanks MM, Washington JK, Oliver GD

707 Reliability and Validity of the HALO Digital Goniometer for Shoulder Range of Motion in Healthy Subjects.
Authors: Correll S, Field J, Hutchinson H, Mickensca G, Pitzammons A, Smoot B

CASE SERIES / STUDIES

Authors: Stevenson VF, Baker RT, Nasopyr A

726 Osteochondritis Dissecans Of The Radial Head In A Young Athlete: A Case Report.
Authors: Mourad F, Muselli F, Patuzzo A, Stracasa A, Filippo L, Dunning J, de las Penas C

LITERATURE REVIEW

737 Rehabilitation Following Isolated Posterior Cruciate Ligament Reconstruction: A Literature Review of Published Protocols.
Authors: Senese M, Greenberg E, Lawrence T, Garley T
<table>
<thead>
<tr>
<th>Page</th>
<th>Article Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>752</td>
<td>Clinical Commentary: Rehabilitation Following Sternoclavicular Joint Reconstruction for Persistent Instability.</td>
<td>Logan C, Shahien A, Altuntas B, Millet PJ</td>
</tr>
</tbody>
</table>
ABSTRACT

Background: There are inconsistencies in the reported rates of second anterior cruciate ligament (ACL) injuries per limb, patients’ sex and graft types after primary ACL reconstruction (ACLR). There are also inconsistencies regarding the influence of these factors on the occurrence of second ACL injury after primary ACLR.

Purpose: To determine the rate of second ACL injury, to either the ipsilateral graft or contralateral healthy ACL, as influenced by sex, age, and graft types and to determine the influence of sex, age, and graft types on the occurrence of second ACL injury after primary ACLR.

Study design: Systematic review and meta-analysis

Methods: A computerized search of MEDLINE, CINAHL, and SPORTDiscus was conducted using combinations of these terms: ACL, ACLR, re-injury, re-rupture, revisions, contralateral tear, ipsilateral graft tear, and second injury. Articles were required to report the number or percentage of sex, graft type, ipsilateral graft and contralateral ACL injuries after ACLR. Rates of second ACL injuries and pooled dichotomous data were calculated using random-effect proportion meta-analysis.

Results: The pooled rate of second ACL injuries (ipsilateral graft and contralateral ACL) was 6.11%. A slightly higher rate of ipsilateral graft injuries (3.29%) than contralateral ACL injuries (2.82%) (OR: 1.09 [95%CI: 0.89, 1.34]) was reported. Ipsilateral graft injuries occurred earlier (median: 20 months) than contralateral ACL injuries (median: 36.3 months). Men had lower rate of second ACL injuries (3.29%) (OR: 0.92 [95%CI: 0.70, 1.20]). Significantly higher rate of ipsilateral graft injuries (3.40%) occurred in men compared to contralateral ACL injuries (2.26%) (OR: 1.53 [95%CI: 1.33, 1.77]), while women had significantly higher rate of contralateral ACL injuries (3.75%) compared to ipsilateral graft injuries (3.09%) (OR: 0.73 [95%CI: 0.55, 0.96]). The rate of second ACL (ipsilateral graft and contralateral ACL) injuries was higher in patients with hamstring tendon (HT) autograft (5.83%) than bone-patella tendon-bone autograft (BPTB) (5.10%) (p=0.04) and allografts (3.12%) (p<0.0001). The rate of ipsilateral graft injuries was significantly higher than contralateral ACL injuries in all graft types (p<0.001).

Conclusion: Injuries to the ipsilateral graft are more common than contralateral ACL, with ipsilateral graft injuries occurring nearly 16 months earlier after ACLR. More women sustain second ACL injuries compared to men, with men incurring more injuries to the ipsilateral graft and women to the contralateral ACL. Furthermore, second ACL injuries are more common in patients with HT autograft, BPTB autograft, and then allograft; with ipsilateral graft injuries higher than contralateral ACL injuries regardless of graft types.

Levels of Evidence: 2a

Key words: Autograft injury, contralateral ACL injury, ipsilateral graft injury, second ACL injury, women re-injury
INTRODUCTION

Early anterior cruciate ligament reconstruction (ACLR) is the standard of care for managing young athletes after initial ACL rupture, as it restores mechanical knee stability, function, and preserves the joint integrity. In the United States alone, up to 175,000 reconstructive surgeries are performed annually. After ACLR, resuming preinjury level of activity without incurring a second anterior cruciate ligament (ACL) injury is considered a successful outcome. Unfortunately, second ACL injuries continue to occur even after successful reconstructive surgery and rehabilitation, with the reported rates of second ACL injuries varying between 3% and 30%. High variability in the reported rates of second ACL injury may be related to inclusion of data from patients with different ages, sex, graft types, activity levels, and different follow-up timeframes after surgery.

Incurring an injury to the ipsilateral graft or contralateral ACL after primary ACLR is devastating for both the patient and medical care providers. This has triggered attention of researchers to focus their investigations on identifying potential risk factors that may account for the occurrence of second ACL injuries. Multiple factors have been reported to be associated with incurring an ipsilateral graft injury. Some patient-related factors include being younger in age and having family history of ACL injury. Surgical-related factors included a vertical graft orientation, small graft size and postoperative knee laxity, and using the hamstring graft. Other factors associated with ipsilateral graft injury include the same mechanism of injury as that at the time of initial ACL injury and patients' physical activities after reconstructive surgery: such as early return to high-demand physical activities and pivoting activities.

After ACLR, the rate of injury for contralateral ACL is comparable to that of ipsilateral graft. A recent systemic review and meta-analysis, investigated the risk of second ACL injury in young athletes after ACLR, found that the rates of ipsilateral graft and contralateral ACL injuries to be 7% and 8%, respectively. Bourke et al, however, reported a higher injury rate to the ipsilateral graft (17%) compared to the contralateral ACL (9.7%). Additionally, Reid et al reported that the rate of ipsilateral graft injury was 9% compared to only 2% in the contralateral ACL. Risk factors that may account for the contralateral ACL injury include the same risk factors that caused the primary ACL injury such as altered lower extremity biomechanics, and the presence of functional deficits after ACLR.

The influence of patients' sex as a risk factor on second ACL injury is still controversial, as it has been reported that men tend to have a high risk of reinjury while women have higher revision rates. Women demonstrate a higher risk of sustaining a primary ACL rupture and second ACL injury to the contralateral limb after ACLR compared to men. Authors of several cohort studies have indicated that men tend to demonstrate an equal to higher risk of incurring an ipsilateral graft injury compared to the contralateral intact ACL after ACLR. Paterno et al reported that, after ACLR, women were four times more likely to sustain an ipsilateral graft injury and six times more likely to acquire a contralateral ACL injury compared to men. Recent systemic reviews have reported that there were no differences between men and women incurring an ipsilateral graft injury. Thus, a systemic review and meta-analysis study could be useful to further investigate the incidence rates of ipsilateral graft and contralateral ACL injuries between sexes.

Second ACL injury has been reported to be associated with various graft types. There is a consensus that allografts have a lower survival rate compared to autografts. However, there is inconsistency in the reported findings for autografts. Tybor et al found similar injury rates between patellar tendon (PT) and hamstring tendon (HT) autografts. Whereas Mohtadi et al found no differences in re-rupture rates between PT and HT autografts. Other authors have reported a higher rate of ipsilateral graft injury in the HT compared to the PT autograft. While graft type is a potential risk factor for graft failure, it has yet to be determined the extent of influence that each type of tissue has on graft failure or injury to the contralateral ACL after ACLR. The importance of determining the failure tendency of the harvested tissue may help the decision-making of which graft type to use during the reconstructive surgery.
Whether the second ACL injury occurs in the ipsilateral graft or contralateral intact ACL, it is an outcome of growing concern with substantial consequences. Although there is currently a significant amount of evidence indicating an increased likelihood of incurring a second ACL injury after primary ACLR, a lack of evidence continues to exist in determining which demographic factors and graft types contribute most to the increased number of second ACL injuries. Conducting a comprehensive data analysis of published studies may help provide an accurate review of ipsilateral graft and contralateral ACL injury rates per patients' age, sex, and graft type. Moreover, it could clarify the influence of these factors on the occurrence of second ACL injuries after primary ACLR. Therefore, the purposes of this systemic review and meta-analysis were (1) to determine the rate of second ACL injury, to either the ipsilateral graft or contralateral healthy ACL, as influenced by sex, age, and graft types and (2) to determine the influence of sex, age, and graft types on the occurrence of second ACL injury after primary ACLR.

MATERIALS AND METHODS

Literature Search

A computerized search was performed for articles on second ACL injury, either to the ipsilateral or contralateral ACL, in patients after primary ACLR. The databases of MEDLINE, CINAHL, and SPORTDiscus were searched for full text articles published in English using combinations and variations of the following terms: ACL, ACLR, re-injury, re-rupture, revisions, contralateral tear, ipsilateral graft tear, and second injury. Authors conducted a broad search in order to capture the majority of articles that reported second ACL injury. The original search revealed 2,029 articles that fit the searched terms. After deleting the duplicated articles, the titles and the abstracts of all identified articles were reviewed for relevance. The search was augmented by cross-checking citations and references of the relevant published articles. In addition to the computerized search, three articles were identified through a hand search of relevant published articles.19,26,49 The search was completed in September 2016 with a total of 41 articles left to be thoroughly read for inclusion criteria. Thirty articles were excluded from this analysis (26 articles did not report graft type or sex, one article was not available in full text, one article included data at a mean follow-up time of 20 years,50 and two articles reported data from the same patients19,24). If articles that reported data for the same patients, the articles that were published earlier were excluded. This resulted in articles by Paterno et al (2014)28 and Webster and Feller(2016)26 being utilized, while Paterno et al (2012)24 and Webster et al (2014)19 were excluded.

Study selection

After all available abstracts were thoroughly examined; the full-text articles were evaluated for inclusion criteria. All articles included in this systematic review and meta-analysis were written in English language and reported the number or percentage of ipsilateral graft and/or contralateral ACL injuries within five years from ACLR. Exclusion criteria included: articles that did not meet any of the previously stated requirements, written in non-English language, had a mean follow-up of more than five years, conference proceedings abstracts, narrative reviews, or clinical commentaries. One article reported follow up of second injury at 2, 5, 10 and 15 years after ACLR, but only data from the 2 and 5 years were included in the analysis of the current analysis.18 While conducting the systematic review and meta-analysis, authors identified articles’ eligibility and inclusion based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Figure 1).
it difficult to determine incidence rate of second injury by age. There was inconsistency among articles regarding the reported data; therefore, the corresponding authors of the included articles were contacted to provide information about number of men, women, and harvested grafts. Additionally, corresponding authors were also asked to provide information regarding the number of ipsilateral graft and contralateral ACL injuries per sex and graft types. Responses with data were received from five authors,\(^17,19,26,49,55\) while another author indicated that the archived data was no longer accessible.\(^52\)

### Statistical Methods

The counts of injuries per limb side, sex, age, and graft type were extracted from each article. The pooled rate of second injury to both the ipsilateral graft and contralateral ACL was calculated by the total number of injured patients to the total number of patients. To determine the pooled rate of second injury in men and women, the pooled number of injured patients of one sex was compared to the total number of patients of that sex. Rates were then calculated for each injured limb side. The pooled rate of second injury for each graft type was calculated by the pooled number of second injury per graft type to the total number of patients who had the same graft type; again, the rates of second ACL injuries were calculated per limb side. Two independent proportions analysis was used to determine the significant differences in second ACL injuries between limb

### Assessment of Studies’ Quality

The methodological quality of the included articles was assessed and rated by two reviewers independently using the Modified Downs and Black checklist (Table 1). This tool is a checklist including 13 items of “yes (Y)” or “no (N)” questions used to assess: 1) the potential sources of bias in non-randomized or cohort studies, 2) the quality of a study, and 3) suggests use of a study in a public health context.\(^51\) The questions are designed to test the studies’ quality, external validity, study bias, confounding and selection bias, and the power of the study. Any discrepancies in the selection process, methodological quality assessment, and data extraction was resolved by discussion or if needed, a third reviewer. A larger total number indicates more satisfied items and thus, articles at less risk of bias.

### Data Extraction/Analysis/Synthesis

Sample size at baseline and follow-up time were recorded for each article. The number of men and women, patients’ age, number of each graft and the reported patients’ demographics were also recorded. The primary variables that were extracted include the number or percentage of ipsilateral graft injuries, number of contralateral ACL injuries, and the time of second injury per sex, graft types, and patients’ age. However, age at injury was unable to be further researched as only two articles grouped their participants based on their ages.\(^17,26\) Age ranges for these articles were overlapping thus making

<table>
<thead>
<tr>
<th>Study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bak et al (1999)(^51)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>10</td>
</tr>
<tr>
<td>Salmon et al (2005)(^11)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>11</td>
</tr>
<tr>
<td>Wright et al (2006)(^57)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>N</td>
<td>9</td>
</tr>
<tr>
<td>Shelbourne et al (2009)(^17)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Bourke et al (2012)(^14)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>8</td>
</tr>
<tr>
<td>Paterno et al (2014)(^36)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>10</td>
</tr>
<tr>
<td>Hejne et al (2015)(^48)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Kaeding et al (2015)(^52)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>12</td>
</tr>
<tr>
<td>Maletis et al (2015)(^39)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Kyritsis et al (2016)(^49)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>8</td>
</tr>
<tr>
<td>Webster and Feller et al (2016)(^26)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>11</td>
</tr>
</tbody>
</table>

Mean study quality was a 9.82 out of a total of 13 points
From the available data, 7,769 (33.04%) of the patients had BPTB autograft, 7,788 (33%) had HT autograft, 7,921 (33.69%) had allograft, and 34 (0.145%) had an iliotibial band autograft.  

Second Injuries by Limb Side  
The pooled rate of second ACL injuries (ipsilateral graft and contralateral ACL) was 6.11% (n=1,441). The pooled rate of ipsilateral graft injuries of 3.29% (n=775) was significantly higher than contralateral ACL injuries of 2.82% (n=666) (p=0.004), with a non-significant pooled odds ratio of 1.09 (95% CI:0.89, 1.34; p=0.38; I²=51.5% [95%CI:0%, 74%]; Harbord-Egger=-1.00 [92.5% CI:-2.52, 0.51] p=0.22) (Figure 2). Of those who had a second ACL injury, 53.8% (775/1,441) of the injuries occurred to the ipsilateral graft and 46.2% (666/1,441) to the contralateral ACL. The pooled relative risk of sustaining an ipsilateral graft injury compared to a contralateral ACL injury was 1.09 (95% CI: 0.09, 1.32) (p=0.38; I²=51.5% [95%CI: 0%, 74%]; Harbord-Egger=-0.95 [92.5% CI:-2.40, 0.51] p=0.22) (Table 2).  

RESULTS  
Demographic  
From the 11 included articles, the pooled number of patients was 24,352, of whom 23,579 patients completed the follow-up (Pooled mean±SD: 45.7±19.38 months; ranges 12-60 months) and were included in this analysis. The pooled mean percentage of men included in the articles [56.15±18.76% (n=14,720)] was significantly higher than that of women [36.54±17.54% (n= 8,859)] (p=0.02) (Table 2), with one article having only men participants. The pooled mean age for participants was 23.96±4.42 years. From the available data, 7,769 (33.04%) of the patients had BPTB autograft, 7,788 (33%) had HT autograft, 7,921 (33.69%) had allograft, and 34 (0.145%) had an iliotibial band autograft.  

<table>
<thead>
<tr>
<th>Study</th>
<th>Age (year)</th>
<th># of patients (women/men)</th>
<th>BPTB</th>
<th>HT</th>
<th>Allograft</th>
<th>Iliotibial band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wright et al (2006)</td>
<td>24(11-54)</td>
<td>235 (125/110)</td>
<td>102</td>
<td>115</td>
<td>17</td>
<td>NR</td>
</tr>
<tr>
<td>Paterno et al (2014)</td>
<td>17.1±3.1</td>
<td>78 (19/59)</td>
<td>39</td>
<td>33</td>
<td>6</td>
<td>NR</td>
</tr>
<tr>
<td>Hejne et al (2015)</td>
<td>29±7/30±9</td>
<td>68 (36/32)</td>
<td>34</td>
<td>34</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Malelts et al (2015)</td>
<td>Median: 27.2(18.7-37.7)</td>
<td>17436 (11111/6325)</td>
<td>4436</td>
<td>5568</td>
<td>7432</td>
<td>NR</td>
</tr>
<tr>
<td>Kyritis et al (2016)</td>
<td>21±4; 22±5</td>
<td>158 (158/0)</td>
<td>50</td>
<td>108</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Webster and Feller et al (2016)</td>
<td>17.2 (11-19)</td>
<td>316 (200/116)</td>
<td>NR</td>
<td>316</td>
<td>NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

BPTB= Bone patellar tendon bone autograft; HT= hamstring tendon autograft; NR= not reported
ipsilateral graft injury compared to a contralateral ACL injury was 1.49 (95% CI: 1.30, 1.71, p<0.0001; I²=0% [95% CI: 0%, 51.2%]; Harbord-Egger=-0.43 [92.5% CI: -1.39, 0.52, p=0.39]).

One article\(^{49}\) did not include women participants and another study\(^{52}\) reported no second ipsilateral graft injury in women. Women had a significantly higher rate of contralateral ACL injuries 3.75% (n=332) than ipsilateral graft injuries 3.09% (n=274) (p=0.016), with pooled odds ratio of ipsilateral graft and contralateral ACL injuries of 0.73 (95% CI:0.55-0.96; p=0.02; I²=40.4% [95% CI:0%, 71.1%]; Harbord-Egger=-1.37 [92.5% CI:-2.77, 0.03], p=0.08) (Figure 4 B). Of injured women, 54.79% of the injuries occurred in the contralateral ACL and 45.21% in the ipsilateral graft. The pooled relative risk for women to sustain a contralateral ACL injury compared to an ipsilateral graft injury was 1.34 (95% CI: 1.04, 1.72, p=0.024; I²=37.9% [95% CI:0%, 70.1%]; Harbord-Egger=1.38 [92.5% CI:0.083, 2.84, p=0.09]).

**Second injuries by Graft Type**

The pooled rate of second ACL injuries in patients with HT autograft of 5.83% (n=454) was significantly higher than in those with BPTB autograft of 5.10% (n=396 (p=0.04) and with allograft of 3.12% (n=247) (p<0.0001). Additionally, the pooled rate of second ACL injuries in patients with BPTB autograft was significantly higher than those with an allograft (p<0.0001). The pooled odds ratio of second ACL

---

**Figure 2.** Pooled odds ratio of ipsilateral graft and contralateral ACL injuries after ACLR regardless of the sex and graft types (Odd ratio, 95% CI, [Random effects]).

**Figure 3.** Pooled odds ratio of second ACL injuries between men and women after ACLR regardless of the limb side and graft types (Odd ratio, 95% CI, [Random effects]).
injuries in HT and BPTB autografts, regardless of the sex, was 1.28 (95% CI: 0.93, 1.76; p=0.058, I²=0% [95% CI: 0%, 58.5%]); Harbord-Egger = -0.27 [92.5% CI: -0.91, 0.37, p=0.39] (Figure 5). The pooled relative risk of patients with HT autograft to sustain a second ACL injury compared to patients with BPTB autograft was 1.16 (95% CI: 0.99, 1.35, p=0.06); I²=0% [95% CI: 0%, 58.5%]; Harbord-Egger = -0.40 [92.5% CI: -1.20, 0.39, p=0.31])

One of the articles reported that six ipsilateral graft injuries occurred in patients who had an autograft; however, the type of the harvested tissue was not specified. Two articles did not use HT autograft and three articles did not use BPTB autograft. The number of ipsilateral graft injuries in patients who had an allograft was reported in four articles (pooled number = 240), and one article reported the second injury in the contralateral ACL (n=7); therefore, determining the pooled odds ratio of ipsilateral and contralateral of allografts was not possible.

The pooled rate of ipsilateral graft injuries in patients with BPTB autograft was significantly higher (2.96%) than that of the contralateral ACL injuries (2.14%) (p=0.001) (Table 3), with pooled odds ratio of injuring ipsilateral graft and contralateral ACL injuries of 1.41 (95% CI: 0.70, 2.83; p=0.34; I²=82.1% [95% CI: 62.3%, 89.2%]; Harbord-Egger = 1.09 [92.5% CI: -5.26, 7.45, p=0.72]) (Figure 6 A). The pooled relative risk of sustaining an ipsilateral graft injury compared to a contralateral ACL injury in patient with BPTB autograft was 1.35 (95% CI: 0.70, 2.61, (p=0.37; I²=81.9%)

<p>| Table 3. Number of Ipsilateral graft and contralateral ACL injuries per graft types |
|--------------------------------------------------|-------------------|-----------------|------------------|---------------|</p>
<table>
<thead>
<tr>
<th>Total number of graft used</th>
<th>Ipsilateral graft injury</th>
<th>Contralateral ACL injury</th>
<th>Total injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPTB autografts</td>
<td>7769</td>
<td>230 (58.08%)</td>
<td>166 (41.92%)</td>
</tr>
<tr>
<td>HT autografts</td>
<td>7788</td>
<td>314 (69.16%)</td>
<td>140 (30.84%)</td>
</tr>
<tr>
<td>Allografts</td>
<td>7921</td>
<td>240 (97.17%)</td>
<td>7 (2.83%)</td>
</tr>
<tr>
<td>Patellar tendon</td>
<td>35</td>
<td>Not reported</td>
<td>Not reported</td>
</tr>
</tbody>
</table>

BPTB= bone patellar tendon bone, HT= hamstring tendon.
to men. With regard to sex, men had a higher rate of ipsilateral graft injuries (3.40%) compared to contralateral ACL injuries (2.26%), while women had a higher rate of contralateral ACL injuries (3.75%) compared to ipsilateral graft injury (3.09). In all graft types, ipsilateral graft injuries were higher than contralateral ACL injuries. Both ipsilateral graft and contralateral ACL injuries were more common in patients with HT autograft followed by those with BPTB autograft, and then allografts.

While the results of this study indicate that more men had second ACL injuries, women had a higher rate of second ACL injuries and were more likely to sustain an injury to their contralateral ACL when compared to men. The trend regarding women being more likely to sustain a second ACL injury to the

![Figure 6. Pooled odds ratio of second ACL injuries in patients with BPTB (Left) and HS (Right) autografts after primary ACLR (Odd ratio, 95% CI) [Random effects].](image)

![Figure 7. Funnel plot for publication bias assessment by Log (Odds ratio).](image)

Publication Bias
The results of Harbord-Egger’s regression tests ranged between -1.37 and 1.09 (p > 0.08) for the odd ratios and between -1.0 and 1.38 (p > 0.09), indicating no publication bias (Figure 7).

DISCUSSION
The purpose of this systemic review and meta-analysis study was to determine the rate of ipsilateral graft and contralateral ACL injuries per patients’ sex and graft types, and to explore the influence of these factors on the occurrence of second ACL injury after primary ACLR. The results of this study indicate that the overall rate of ipsilateral graft injuries was higher than the contralateral ACL injuries, regardless of sex and graft types. Ipsilateral graft injuries on average occurred earlier than the contralateral ACL injuries after primary ACLR. Additionally, the rate of second ACL injuries was higher in women compared
contralateral ACL in this study is similar to what has previously been reported in several studies.\textsuperscript{17,24,35,38,39} High rates of contralateral ACL injuries in women may have resulted from adapting a protective strategy to compensate for the reconstructed limb due to the lack of confidence and fear of sustaining further injury to the reconstructed knee.\textsuperscript{60–62} As a response, women may have tended to rely mainly on their contralateral (uninjured) limb during participation in daily living and physical activities. This, in turn, may have placed an excessive load on the uninjured contralateral ACL, that over time may cause an overuse and fatigue leading to complete rupture.\textsuperscript{62} Further, women may have continued to exhibit unresolved neuromuscular and biomechanical deficits that may contribute to injuring the contralateral ACL.\textsuperscript{9,28–34}

Overall, men were more likely to sustain an injury to their ipsilateral graft compared to women and the results of this study provide evidence that men are at a higher risk to injure their ipsilateral graft than the contralateral ACL. The findings of the current study support the findings of previous studies that found a high ipsilateral graft injury in men compared to women.\textsuperscript{26,38} Unfortunately, the results of the current systematic review and meta-analysis do not explain why men demonstrate a higher risk for sustaining an injury to the ipsilateral graft. These injuries may be due to the number of men who return to participate in high-demand physical activities after ACLR as compared to women. Authors in previous studies have reported that younger men are more likely to return to their preinjury level of sports, which include mainly cutting and pivoting activities.\textsuperscript{13,63} Therefore, men returning to sport activities may, as a consequence, expose the newly harvested graft to an excessive mechanical load thus resulting in ipsilateral graft failure.

The results of the current study agree that ipsilateral graft injury occurred earlier post-operatively than the contralateral ACL injury, similar to what has been previously reported in other studies.\textsuperscript{11,17,18,26,38,49,59,64} Paterno and colleagues\textsuperscript{38} reported that 50% of the athletes with second ACL injuries sustained their injury during the first 72 sport exposures. After ACLR, the graft tissues undergo remodeling processes during the first year, which may affect the mechanical properties of the harvested graft tissue. Although, functional deficits may have been resolved prior to returning to high-demand physical activities, exposing the harvested graft (which continues to mature over time) to high loading may lead to graft failure. Recently, Nageli and Hewett recommended delaying return to sport activities for up to two years in order to preserve the graft tissue.\textsuperscript{65}

Sustaining a second ACL injury, either to the ipsilateral graft or contralateral ACL, is devastating for both the injured patient and health care providers. While it is unclear why the second injury occurred, early return to high-level sport activities may put patient more at risk.\textsuperscript{13,25,63,66} Early (≤ 9 months after ACLR) return to sport and participation in high demand physical activities without fully resolving the patients’ functional deficits may contribute to second ACL injury.\textsuperscript{29,67,68} Several authors have reported that young athletes (≤ 25 years)\textsuperscript{25} who return to sports are at risk for sustaining a second ACL injury.\textsuperscript{11,15,17,19,25,64,69} Other factors that may also contribute to a second ACL injury include, but are not restricted to, the risk factors that caused the primary ACL injury,\textsuperscript{9,70} inadequate rehabilitation after ACLR, returning to participate in physical activities without being rehabilitated to meet the demand of the activities,\textsuperscript{34,71–76} or clearing patients to return to their activities without using robust objective criteria that are sensitive to determine the patients’ physical deficits.\textsuperscript{29,67,77–79}

In this analysis, only four out of 11 articles reported using an allograft for reconstructive surgery. Patients who had an allograft sustained more injuries to the ipsilateral graft than to the contralateral ACL. This finding is consistent with what has been reported in the literature. However, computing the odds ratio for patients who had an allograft (between ipsilateral and contralateral limbs) was not possible due to the small number of studies that reported use of an allograft, of which only one reported a contralateral ACL injury. Fewer studies reporting the use of an allograft might be due to the fact that the current standard for graft option is an autograft instead of an allograft.\textsuperscript{90–92}

Second ACL injuries, after primary ACLR, were more common in patients with hamstring tendon autograft followed by BPTB autograft, and then allograft.
et al. reported that anatomical differences between men and women continue to play a role in sustaining a second injury. After ACL reconstruction, the graft is typically larger than the native ACL in women; therefore, a potential risk of injury to the contralateral limb is present since it is comparatively “smaller” and unable to sustain the same amount of tensile forces as the reconstructed ligament. However, the opposite may be true in men, thus placing them at an increased risk of second injury to the ipsilateral limb.

Articles were appraised using a modified checklist to assess the potential sources of bias and the quality of a study. All articles were scored at eight or higher out of a total possible score of 13, suggesting that all included articles were of acceptable to high quality. Additionally, a random effects model was performed to account for heterogeneity or variability explained by the difference between included studies. This allowed the authors to account for any unexplained heterogeneity between studies and provide an estimate of the odds ratio for each outcome variable.

Limitations
The articles included in this meta-analysis reported findings from data collected within the first five years after ACLR. Thereby, one limitation of this meta-analysis is that the rates of second ACL injuries per limb side, sex, and graft type are not time-specific as second ACL injury may have occurred at any time within the five years after surgery. This, in turn, may limit the generalizability of this study's findings to a specific follow-up time after ACLR. Another limitation of this meta-analysis was related to the inconsistency in the reported data and findings across articles regarding the patients' age, number of men and women, and time of follow-ups. This may cause a publication bias that led to underestimating the rate of second ACL injuries. In this meta-analysis, however, publication bias does not appear to be an issue as Harbord-Egger test was not significant for any of the measures at a confidence interval of 92.5%. The articles included in the meta-analysis did not consistently report the second ACL injury per limb side, sex, graft type, and the mechanism of injury for the primary ACL injury which prevented advanced statistical analysis to account for or discern the influence of multiple factors simultaneously.

Furthermore, patients who had hamstring tendon autograft, BPTB autograft, or allograft demonstrated higher ipsilateral graft injury compared to the contralateral ACL injury. Patients with HT autograft were more likely to sustain an ipsilateral graft injury compared to contralateral ACL injury, with an odds ratio of 2.22 for patients with HS autograft injuring their ipsilateral graft compared to the contralateral ACL. The results of this study support the findings of previous studies that report HT autograft patients sustain more second ACL injury compared to BPTB autograft patients. The studies included in this meta-analysis did not report the ipsilateral graft injury per sex. Therefore, stratifying second ACL injuries between sexes per graft types was not possible.

Although this systematic review and meta-analysis studied only the influence of patients' sex and graft types on ipsilateral graft and contralateral ACL injuries, other studies have indicated an influence of BMI, race, graft size, family history, age, abnormal joint biomechanics, and return to activity levels on second ACL injury. Bourke et al. noted a correlation between family history of ACL ruptures and second injury to the ipsilateral limb. As reported by Maletis et al., higher BMI could contribute to decreased risk for second ACL injuries, potentially due to the fact that patients of higher BMI do not return to sport or high level activities. Maletis et al. also noted that patients of African-American descent had a lower risk of second injury; however, the researchers were unable to determine the reasons for this observation. Many of the risk factors appraised in the articles are non-modifiable factors including sex, race, and family history. Other risk factors are modifiable at the time of the surgical procedure, during the post-surgical rehabilitation, or during the decision-making process to clear patients for return to preinjury activity levels. Bourke et al. indicated that a higher risk of contralateral injury might be due to an overall lack of a central protective mechanism after primary ACL injury. Bourke et al. noted that there might be high “cost” to the body when harvesting the BPTB compared to the HT which, in return, produces greater neuromuscular control deficits. Kaeding et al. attributed the increased risk of ipsilateral second injury with use of HT autografts to the decreased graft diameter compared to BPTB autografts. Similarly, Shelbourne et al. reported that anatomical differences between men and women continue to play a role in sustaining a second injury. After ACL reconstruction, the graft is typically larger than the native ACL in women; therefore, a potential risk of injury to the contralateral limb is present since it is comparatively “smaller” and unable to sustain the same amount of tensile forces as the reconstructed ligament. However, the opposite may be true in men, thus placing them at an increased risk of second injury to the ipsilateral limb.
additional limitation was associated with the reporting of mechanism of injury for the second ACL injury, only two articles reported the contact mechanism of injury for the second ACL injuries (Salmon 2005 [ipsilateral graft injury:17; contralateral ACL:10]; Webster 2014 [ipsilateral graft injury:16; contralateral ACL injury:15]) and only three articles reported the non-contact mechanism of injury for the second ACL injury (Salmon 2005 [graft injury:22; contralateral ACL:25]; Webster 2014 [graft injury:10; contralateral ACL injury:26]; and Paterno [23 injuries, but did not specify for graft and contralateral ACL injuries]. Further, this study is limited as to whether the patients of the included articles did or did not return to their preinjury sport participation, because it was not reported. Further studies may consider investigating the impact of returning to the preinjury sport activities on the incidence of second ACL injury. A final limitation was related to the lack of a uniform method used to confirm a second ACL injury.

CONCLUSIONS
The results of this systematic review and meta-analysis indicate that ipsilateral graft injury occurs more frequent than a contralateral ACL injury after primary ACLR, regardless of the sex and graft type, with ipsilateral graft injuries occurring earlier (postoperatively) than contralateral injuries. Second ACL injury of both ipsilateral graft and contralateral ACL are more common among women compared to men. Men are more likely to sustain an injury to ipsilateral graft while women are more likely to sustain an injury to the contralateral ACL. Patients with HT autograft demonstrate a higher rate of sustaining a second ACL injury to either limb, followed by patients with BPTB autograft, and allograft respectively. Regardless of graft type, ipsilateral graft injuries are more common than contralateral injuries.

REFERENCES
15. Lind M, Menhert F, Pedersen AB. Incidence and outcome after revision anterior cruciate ligament


78. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697-1705.


ABSTRACT

Background: With the increasing number of individuals participating in sports every year, injury - specifically anterior cruciate ligament (ACL) injury - remains an inherent risk factor for participants. The majority of ACL injuries occur from a non-contact mechanism, and there is a high physical and financial burden associated with injury. Understanding the risk factors for ACL injury may aid in the development of prevention efforts.

Purpose: The purpose of this review was to synthesize and appraise existing literature for risk factors associated with non-contact anterior cruciate ligament (ACL) injury in both sexes.

Study Design: Systematic review.

Methods: An electronic literature search was conducted utilizing the MEDLINE database and The Cochrane library for articles available through February 2016. All titles and abstracts were reviewed and full text articles meeting eligibility criteria were assessed in detail to determine inclusion or exclusion. Articles reviewed in full text were reviewed for scientific evidence of risk factors for ACL injury. Results from studies were extracted and initially classified as either intrinsic or extrinsic risk factors, and then further categorized based upon the evidence presented in the studies meeting inclusion criteria. Data extracted from eligible studies included general study characteristics (study design, sample characteristics), methodology, and results for risk factors included.

Results: Principal findings of this systematic review identified the following risk factors for ACL injury in both sexes: degrading weather conditions, decreased intercondylar notch index or width, increased lateral or posterior tibial plateau slope, decreased core and hip strength, and potential genetic influence.

Conclusions: Neuromuscular and biomechanical risk factors may be addressed through neuromuscular preventative training programs. Though some extrinsic and other inherent physiological factors tend to be non-modifiable, attempts to improve upon those modifiable factors may lead to a decreased incidence of ACL injury.

Level of Evidence: 2a.

Key Words: anterior cruciate ligament, ACL, risk factor, injury, rupture.

The authors of this manuscript have no conflict of interests to report.
INTRODUCTION

Over 212 million individuals worldwide participate in competitive or leisure time sports activities. There is an inherent risk of injury for sport participants, due to the nature of competition and the physiological requirements placed on the body. While contact may play a factor, over 70% of anterior cruciate ligament (ACL) injuries occur with a non-contact mechanism, with an estimated 100,000 Injuries per year within the National Collegiate Athletic Association (NCAA) alone. A review of ACL injuries from the NCAA revealed that the highest rate of injury in men occurred in football (0.17 per 1000 Athlete-Exposures [A-E]), while for women, basketball and lacrosse show the highest rate of injury (0.23 per 1000 A-E). Surgical reconstruction stands as the most common treatment option for complete ACL rupture. The cost of ACL injury comes in the form of lost participation time as well as monetary cost of reconstructive surgery. The cost of a reconstructive ACL surgery averages $12,740, with lifetime societal costs (e.g. disability, decreased productivity) upwards of $38,000.

Due to the high individual and societal costs associated with ACL injury, and the catastrophic impact to an individual’s quality of life, prevention of this condition should continue to be a primary concern. Prevention begins with an understanding of risk factors associated with ACL injury. Risk factors that predispose an individual for injury are categorized as intrinsic or extrinsic. Intrinsic factors, those inherent to the individual, are further subdivided as either modifiable or non-modifiable. Modifiable risk factors are those that may be altered in the individual (e.g. muscular strength or flexibility). Non-modifiable risk factors include those which are intrinsic and cannot be controlled by the individual (e.g. anatomical structure). Extrinsic risk factors are those that are outside of the control of the individual (e.g. playing surface). Due to extrinsic and non-modifiable intrinsic factors, the risk of ACL injury will always exist. The opportunity to reduce the prevalence of ACL injury may be achieved by employing preventative measures derived from the knowledge of modifiable risk factors. Currently, preventative programs have shown promise for the reduction of ACL injury risk in sport. Previously, systematic reviews have addressed the risk factors associated with only one sex, with insignificant cross comparison. Aggregating the current literature of risk factors for ACL injury for both sexes provides the unique opportunity to address factors across the population, and to identify those that require more individualistic approaches. Therefore, the purpose of this systematic review was to synthesize and appraise existing literature for risk factors associated with non-contact ACL injury in both sexes.

METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for systematic reviews was utilized for reporting in this study. Initial criterion for inclusion in this review was observational, prospective, or retrospective human studies which investigated risk factors for injury to the ACL. Additional inclusion criteria included those written in the English language and those with a level of evidence between I and IV. Studies that did not utilize non-contact ACL injury as an outcome or did not use ACL injured participants were excluded. Studies identifying secondary or tertiary factors related to ACL injury were excluded. Both diagnostic and therapeutic studies were excluded; i.e. studies investigating roles of preventative interventions investigating potential risk reduction. Studies that did not present significant findings of association of risk from potential factors were excluded. Previous systematic review, meta-analyses, and review articles were excluded. Studies not written in the English language were excluded, and there were no population restrictions utilized during the search.

Data Sources

An electronic literature search was conducted utilizing the MEDLINE database and The Cochrane library for all articles available through February 2016. The literature search was conducted utilizing search strategies (inclusion & exclusion) and keywords modeled from prior systematic reviews, and these are summarized in Table 1.

Study Selection & Data Extraction

All titles and abstracts were reviewed and full text articles meeting eligibility criteria were assessed in
detail to determine inclusion or exclusion. Abstracts and articles were reviewed for inclusion by two authors, and upon any discrepancies, a third author would provide a ruling. The search of the literature resulted in a total of 381 references; of which one was a duplicate and another 301 studies were excluded (Figure 1). A total of 79 full text articles were reviewed, 55 of which met criteria for inclusion and were subsequently incorporated. Articles reviewed in full text were reviewed for the presence of inclusion criteria, specifically for scientific evidence of risk factors for potential ACL injury. Results from studies were extracted and initially classified as either intrinsic or extrinsic risk factors. Extrinsic risk factors were further categorized into weather, playing surface, sport level, ski type, and participation level. Intrinsic risk factors were labeled as anatomical, neuromuscular, biomechanical, physiologic, and genetic. Data extracted from eligible studies included general study characteristics (study design, sample characteristics), methodology, and results for risk factors included.

**Assessment of quality**

Assessment of risk of bias for the studies included was performed utilizing previously established criteria from Alentorn-Geli et al. (Table 2). A quality score was assigned for each study included, utilizing each ‘yes’ as one point toward the studies score and other responses receiving no points. Higher quality scores indicated studies with a greater methodological rigor.

---

**Table 1. Systematic search strategies and keywords.**

<table>
<thead>
<tr>
<th>Database</th>
<th>Search</th>
<th>Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pubmed</td>
<td>1</td>
<td>(risk) OR risk of</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(injury OR injuries OR tear OR tears OR tearing OR rupture OR rupture OR sprain OR sprains)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>(anterior cruciate ligament or ACL)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>((((prospective) OR randomized controlled trial) OR cohort) OR Case control) OR case-control) OR longitudinal</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>#1 AND #2 AND #3 AND #4</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>reconstruction</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>#5 NOT #6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>(animals) NOT (animals AND humans)</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>#7 NOT #8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(editorial) OR letter) OR comment</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>#9 NOT #10</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>#9 NOT #10: Filters: English</td>
</tr>
<tr>
<td>Cochrane</td>
<td>1</td>
<td>(risk) OR risk of</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>MeSH descriptor: [Anterior Cruciate Ligament] explode all trees</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>anterior cruciate ligament OR ACL (word variations have been searched)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>#2 or #3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>MeSH descriptor: [Wounds and Injuries] explode all trees</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Injuries OR Injury OR tear OR tears OR tearing OR rupture OR ruptures OR sprain OR sprains (word variations have been searched)</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>#5 or #6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>prospective OR randomized controlled trial OR cohort OR case control OR case-control (word variations have been searched)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>animals NOT (animals AND humans)</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>editorial OR letter OR comment</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>#1 AND #4 AND #7 AND #8 NOT #10 NOT #11</td>
</tr>
</tbody>
</table>
RESULTS
Summary of risk of bias
In general, studies involved in this systematic review appear to have a moderate risk of bias. Of the involved studies, there was a high proportion of unreported information relating to the assessment of risk of bias and quality score.

Extrinsic Risk Factors
There were a total of 10 risk factors identified which were subsequently categorized as extrinsic: five related to weather, two to playing surface, one sport level, one ski type, and one participation level (Table 3).

Three studies identified risk factors for ACL injury stemming from weather conditions. Two studies by Orchard et al.\textsuperscript{19,20} examined the weather conditions surrounding matches of Australian football over several years of match play. It was determined that a high evaporation rate for 28 days leading up to the match date placed individuals at a higher risk for injury (RR = 2.8).\textsuperscript{19} Both studies reported that low rainfall in the year preceding matches increased the risk of injury (RR = 1.5 to 1.93).\textsuperscript{19,20} Additionally, the absence of rainfall during matches placed those playing at a higher risk of injury (RR = 1.55).\textsuperscript{20} The last weather-related study reported female recreational skiers were at an increased risk of injury while in icy snow conditions (OR = 24.33) or while skiing during snowfall (OR = 16.63).\textsuperscript{21}

Two studies identified the type of playing surface as a risk factor for injury. In 2002, Pope et al.\textsuperscript{22} found that rubber matting on a military obstacle course was correlated with the number of ACL injuries sustained in the Australian army ($\chi^2 = 4.76$).\textsuperscript{22} Orchard et al.\textsuperscript{20} found that in Australian football, individuals participating on fields with Bermuda grass are at an increased risk (RR = 1.87).\textsuperscript{20} Other risk factors included: the use of traditional skis (versus carving skis) for recreational female skiers (OR = 10.49),\textsuperscript{21} increased sport participation sessions per week (adolescents; < 3 days per week female and male Hazard Ratio = 2.0; > 4 days per week, female, male Hazard Ratio = 8.5, 4.0),\textsuperscript{23} and individuals who participated in collegiate sports were at an increased risk of injury compared to high school sport participants (RR = 2.38).\textsuperscript{24}

The identified weather-related and playing surface factors are out of an individual’s control, however, some of these factors (i.e. playing surface) may be modified by the overseeing organizations. The risk factor of participation level may be modified by an individual (i.e. self-regulating participation), though typically this along with sport level may be predeter-
dined and interlinked factors. The type of ski use in recreational skier is modifiable and reliant on individual choice.

Intrinsic Risk Factors
There were a total of 37 risk intrinsic factors identified in the review of literature. The risk factors were further subdivided in to 17 anatomic, eight neuromuscular, six physiologic, three biomechanical, and one genetic. The final two risk identified factors did not align with prior categorizations (Table 3).

Anatomic Factors
In multiple studies it has been reported that individuals who sustain ACL injury have intercondylar notch stenosis or a narrow intercondylar notch as determined by notch width index.\textsuperscript{25-29} Furthermore, for each millimeter decrease in the
Table 2. Assessment of risk of bias.

| Author                  | A | B | C | D | E | F | G | H | I | J | K | L | M | No | Score |
|-------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|-----|-------|
| Alentorn-Gei 2015       | No| No| Yes| U| No| No| U| No| U| U| U| U| U| Yes| 2   |
| Beynonn 2006           | No| No| Yes| No| No| No| Yes| U| U| U| No| U| NA| Yes| 3   |
| Beynonn 2014a          | No| No| Yes| U| No| U| U| Yes| Yes| U| No| U| Yes| 3   |
| Beynonn 2014b          | No| No| Yes| No| U| No| U| Yes| Yes| U| Yes| U| No| 4   |
| Beynonn 2014c          | No| No| No| No| No| U| Yes| No| U| No| U| NA| U  | 1   |
| Bisson 2010            | No| U| No| No| No| No| U| Yes| No| U| No| U| NA| Yes| 3   |
| Chaudhuri 2009         | No| U| Yes| U| U| U| U| Yes| Yes| U| No| NA| NA| Yes| 3   |
| Dare 2015              | No| U| Yes| U| U| U| U| Yes| Yes| U| No| U| No| Yes| 3   |
| Everhart 2010          | No| No| Yes| No| U| Yes| Yes| No| U| No| U| NA| U  | 4   |
| Fernández-Jaén 2015    | No| No| Yes| No| U| No| U| No| U| No| U| NA| Yes| 2   |
| Flynn 2005             | No| No| U| U| No| No| No| No| No| No| No| U| No| 0   |
| Häggquist 2016         | Yes| U| U| U| U| No| No| U| No| U| No| No| NA| Yes| 3   |
| Hewett 2005            | Yes| U| Yes| U| U| U| U| No| U| No| U| No| U| Yes| 3   |
| Khayambashi 2016       | Yes| U| No| U| U| U| Yes| Yes| U| Yes| Yes| U| No| 5   |
| Khoshchou 2008         | No| No| U| U| U| No| U| No| U| No| U| No| NA| Yes| 1   |
| Kramer 2007            | Yes| No| Yes| No| Yes| Yes| No| No| No| NA| NA| Yes| NA| Yes| 6   |
| LaPrade 1994           | Yes| U| U| No| U| U| U| No| U| No| U| U| Yes| 2   |
| Lefere 2013            | No| No| U| U| U| U| U| U| No| U| No| U| No| 0   |
| Lund-Hassan 1994       | No| No| U| U| U| U| U| No| U| No| U| No| NA| Yes| 1   |
| Mannion 2014           | No| U| No| No| No| No| No| No| No| U| No| U| NA| No| 2   |
| Myer 2009b             | Yes| U| Yes| No| U| U| U| Yes| Yes| No| U| No| U| No| 3   |
| Myer 2015              | Yes| U| No| No| U| U| U| No| U| No| No| U| No| U| 1   |
| Nilsson 2014           | Yes| No| No| U| No| U| U| No| Yes| No| No| NA| No| 2   |
| O’Connell 2015         | No| U| U| U| U| U| U| No| No| U| No| U| Yes| 1   |
| Orchard 1999           | U| No| U| U| U| U| U| No| No| No| No| U| NA| U  | 0   |
| Orchard 2005           | No| No| U| U| U| U| U| Yes| No| No| No| NA| NA| U  | 1   |
| Pope 2002              | Yes| U| NA| NA| U| U| Yes| No| No| Yes| No| U| No| U| 3   |
| Posthumus 2009         | No| U| No| No| U| U| U| No| No| NA| NA| NA| Yes| 1   |
| Posthumus 2010         | No| No| Yes| No| No| No| No| No| No| U| No| U| NA| Yes| 2   |
| Posthumus 2009b        | No| No| Yes| No| U| No| No| No| Yes| No| No| U| NA| U  | 2   |
| Posthumus 2012         | No| No| Yes| No| No| No| No| No| Yes| No| U| No| NA| Yes| 3   |
| Quatman 2011           | Yes| U| U| U| U| U| U| No| No| No| No| NA| NA| Yes| 2   |
| Raschner 2012          | No| U| U| No| U| U| No| U| No| U| U| U| U| No| 0   |
| Ruedi 2009             | No| No| U| U| U| U| U| No| U| No| U| U| Yes| 1   |
| Ruedi 2011             | No| No| No| U| U| U| U| No| No| U| No| U| Yes| 1   |
| Ruedi 2012             | No| No| No| No| No| No| U| Yes| No| No| NA| NA| NA| Yes| 2   |
| Saper 2016             | No| U| No| U| U| U| Yes| No| U| No| NA| Yes| 2   |
| Shaw 2015              | No| U| U| No| U| U| U| Yes| U| U| No| U| NA| Yes| 2   |
| Simon 2010             | No| U| U| U| U| U| U| Yes| U| No| NA| NA| Yes| 2   |
| Souryal 1993           | Yes| No| U| NA| U| Yes| Yes| Yes| No| U| No| Yes| Yes| No| 6   |
| Stijak 2014            | No| No| U| U| U| U| U| Yes| Yes| U| No| U| NA| Yes| 2   |
| Sturck 2014a           | U| U| U| U| U| U| Yes| Yes| U| NA| NA| NA| U  | 2   |
| Sturck 2014b           | Yes| U| U| U| U| U| Yes| Yes| U| No| NA| Yes| 3   |
| Sturck 2015            | No| U| U| No| No| No| No| No| Yes| U| No| U| Yes| 1   |
| Tainaka 2014           | No| No| Yes| U| Yes| U| U| Yes| U| No| U| No| NA| U  | 3   |
| Terauch 2011           | No| No| U| No| No| No| No| No| Yes| U| No| U| NA| Yes| 2   |
| Todd 2010              | No| No| Yes| U| NA| U| No| Yes| No| U| No| U| NA| Yes| 3   |
| Uhorchak 2003          | Yes| No| U| No| Yes| Yes| Yes| Yes| No| U| Yes| Yes| No| Yes| 8   |
| Vyas 2011              | No| No| No| U| U| U| U| No| U| No| U| No| NA| Yes| 1   |
| Whitney 2014           | No| No| No| No| No| No| U| Yes| U| U| No| U| NA| U  | 1   |
| Xiao 2016              | Yes| U| Yes| U| U| U| Yes| No| U| No| NA| Yes| 3   |
| Zazuval 2007           | Yes| No| Yes| U| Yes| Yes| Yes| No| No| U| No| U| Yes| U  | 6   |
| Zibis 2009             | Yes| No| U| No| U| U| Yes| No| No| No| No| No| No| Yes| 3   |
| Zeng 2014              | No| No| U| Yes| Yes| Yes| Yes| Yes| Yes| U| No| U| No| Yes| 6   |

Column Abbreviations: A=Prospective study; B=Concealed/blind group assignment; C=Group similarities at baseline; D=participant blinding; E=data collector blindng; F=outcome assessor blinding; G=previous knee injuries excluded; H=results specified for non-contact; I=no influence of other risk factors; J=acceptable compliance; K=drop out reasons reported; L=acceptable dropout rate; M=duration of intervention comparable; N=intention to treat analysis.

Yes= criteria was explained and acceptable (1 point); No= criteria missing or not acceptable (0 points); U= Unknown, criteria not explained or unclear; NA = not applicable (0 points).
<table>
<thead>
<tr>
<th>Category</th>
<th>Risk Factor*</th>
<th>Sex</th>
<th>N</th>
<th>Quality*</th>
<th>Studies</th>
<th>Risk assessment</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extrinsic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weather conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>During snowfall (skiing)</td>
<td>F</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.1.26-2.77</td>
</tr>
<tr>
<td>Icy conditions (skiing)</td>
<td>F</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.3.34-3.46</td>
</tr>
<tr>
<td>High 28 day evaporation rate</td>
<td>M</td>
<td>1</td>
<td>0 (0)</td>
<td></td>
<td></td>
<td></td>
<td>2.3.5-3.56</td>
</tr>
<tr>
<td>No rainfall during match (wet ground)</td>
<td>M</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.1.51-1.56</td>
</tr>
<tr>
<td>Low previous year rainfall</td>
<td>M</td>
<td>1</td>
<td>0.5 (0-1)</td>
<td></td>
<td></td>
<td></td>
<td>1.1.51-1.56</td>
</tr>
<tr>
<td><strong>Playing surface</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber matting (military obstacle course)</td>
<td>B</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.1-1.4</td>
</tr>
<tr>
<td>Bermuda Grass</td>
<td>M</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.2.6-3.7</td>
</tr>
<tr>
<td><strong>Sport level</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>College level (compared to high school)</td>
<td>B</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.2.5-3.4</td>
</tr>
<tr>
<td><strong>Ski Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional ski</td>
<td>F</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>2.2.2-3.2</td>
</tr>
<tr>
<td><strong>Sport participation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greater weekly sport participation (≥ 4 time/week)</td>
<td>B</td>
<td>1</td>
<td>3 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.4.3-4.6</td>
</tr>
<tr>
<td><strong>Intrinsic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-dominant leg injury</td>
<td>F</td>
<td>2</td>
<td>2.5 (2-3)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.3-1.6</td>
</tr>
<tr>
<td>Generalized joint laxity</td>
<td>B</td>
<td>2</td>
<td>7 (6-8)</td>
<td></td>
<td></td>
<td></td>
<td>1.3.5-3.7</td>
</tr>
<tr>
<td>Genu Recurvatum</td>
<td>F</td>
<td>1</td>
<td>6 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.3.4-3.5</td>
</tr>
<tr>
<td>Decreased ACL width</td>
<td>B</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.4.5-5.6</td>
</tr>
<tr>
<td>Increased ACL length</td>
<td>B</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Anatomic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased notch width or notch width index</td>
<td>B</td>
<td>11</td>
<td>2.9 (1-8)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.9-1.9</td>
</tr>
<tr>
<td>ACL volume (decreased)</td>
<td>B</td>
<td>2</td>
<td>1.5 (1-3)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.7-0.9</td>
</tr>
<tr>
<td><strong>Greater alpha angle</strong></td>
<td>B</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.5.1-2.6</td>
</tr>
<tr>
<td>Increased tibial tuberosity to trochanteric distance</td>
<td>B</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.4-1.7</td>
</tr>
<tr>
<td>Increased medial tibial plateau depth</td>
<td>B</td>
<td>3</td>
<td>4 (2-3)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.0-1.0</td>
</tr>
<tr>
<td><strong>Increased lateral tibial plateau depth</strong></td>
<td>M</td>
<td>1</td>
<td>3 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Increased lateral or posterior tibial plateau slope</td>
<td>B</td>
<td>9</td>
<td>2.8 (1-6)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.7-1.5</td>
</tr>
<tr>
<td><strong>Increased femoral plateau angle</strong></td>
<td>F</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Increased medial tibial slope (open physia)</strong></td>
<td>B</td>
<td>1</td>
<td>1 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Conflicting Evidence</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased medial tibial spine width/volume</td>
<td>B</td>
<td>2</td>
<td>5 (2-8)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.7-1.5</td>
</tr>
<tr>
<td>Increased thickness of intercondylar notch bony ridge</td>
<td>B</td>
<td>2</td>
<td>2.5 (1-4)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.7-1.5</td>
</tr>
<tr>
<td>Lateral middle cartilage slope</td>
<td>B</td>
<td>2</td>
<td>1.5 (1-3)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Neuromuscular</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased resistance to fatigue</td>
<td>M</td>
<td>1</td>
<td>2 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Altered EMG muscular pre-activity</td>
<td>F</td>
<td>1</td>
<td>3 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Core stability</td>
<td>F</td>
<td>1</td>
<td>6 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Decreased knee abductor strength</td>
<td>B</td>
<td>1</td>
<td>5 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.5-1.2</td>
</tr>
<tr>
<td>Decreased hip external rotation strength</td>
<td>B</td>
<td>1</td>
<td>5 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.8-1.3</td>
</tr>
<tr>
<td>Decreased hamstrings strength</td>
<td>F</td>
<td>1</td>
<td>3 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Multi-Factor strength</td>
<td>B</td>
<td>1</td>
<td>0 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Iliotibial band flexibility</td>
<td>F</td>
<td>1</td>
<td>6 (0)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Biomechanical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased knee abduction moment and angle on landing</td>
<td>F</td>
<td>2</td>
<td>2 (1-3)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Increased knee valgus on landing</td>
<td>F</td>
<td>2</td>
<td>2.5 (2-3)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Decreased hip external (ER) &amp; internal (IR) rotation</td>
<td>B</td>
<td>1</td>
<td>3 (0)</td>
<td></td>
<td></td>
<td></td>
<td>1.0.10-0.34</td>
</tr>
</tbody>
</table>

*The International Journal of Sports Physical Therapy | Volume 13, Number 4 | August 2018 | Page S80
anterior intercondylar notch width females were at an increased risk (OR = 1.5) compared to males.\textsuperscript{30} This risk factor has been reported in various populations, such as female handball players with a narrow intercondylar notch (OR = 7.0).\textsuperscript{31} In both female and male army cadets, a narrow notch width (determined by notch width index one standard deviation below the mean) (OR = 3.8) increases the risk of ACL injury.\textsuperscript{12} One study demonstrated that individuals with a narrow intercondylar notch inlet (where ACL enters intercondylar notch posteriorly) was smaller for ACL injured individuals, and this measurement alone demonstrated a positive predictive value of 70%.\textsuperscript{32} Additionally, in the pediatric population individuals who sustained ACL injury have a significantly smaller notch width index when compared to their uninjured peers.\textsuperscript{33}

An increased posterior or lateral tibial slope was identified in nine studies as more prevalent in individuals with an ACL deficient knee when compared to uninjured peers.\textsuperscript{32,34-41} Two studies presented conflicting data with ACL injured individuals having either an increased (OR = 1.324)\textsuperscript{30} or decreased (OR = 1.155)\textsuperscript{37} lateral compartment middle cartilage slope. Additionally, one study specified that females with an increased lateral slope are 1.2 times as likely to sustain injury.\textsuperscript{41} Individuals who had an open lower extremity physis were categorized into the pediatric population, and in those individuals with an open physis an increased medial tibial slope has been identified as an additional risk factor.\textsuperscript{43} One study identified an increased femoral plateau angle (defined as the angle between a line tangent to the anterior femoral cortex and a line extended from the peaks of the medial tibial plateau) to be present in those female individuals who have suffered ACL injury.\textsuperscript{39} Increases of an individual’s alpha angle (measured from sagittal view films, intercondylar notch roof by the long axis of femur), distance between their tibial tuberosity and trochlear groove,\textsuperscript{44} depth of the medial tibial plateau,\textsuperscript{33-35} depth of the lateral tibial plateau,\textsuperscript{34} and a generalize joint laxity may predispose athletes for injury to the ACL.\textsuperscript{12,45} The presence of genu recurvatum is related to a history of ACL injury, and may be a secondary factor in generalized joint laxity.\textsuperscript{45} Characteristics related directly to the ligament, a decreased width,\textsuperscript{46} decreased volume (size of ligament),\textsuperscript{47,48} and an increased length were reported to be predisposing factors for injury.\textsuperscript{46} There is also conflicting evidence regarding the bony ridge within the intercondylar notch as a risk factor. Two studies reported that a decreased medial tibial spine width or volume (OR = 1.5 for each 100mm decrease) placed individuals at increased likelihood of injury,\textsuperscript{12,36} while two other studies found an
increased thickness of the bony ridge in the inter-condylar notch (OR=1.614) to increase likelihood of injury.\textsuperscript{29,47} It may be generally agreed that risk factors related to an individual's anatomical structure are non-modifiable.\textsuperscript{49}

**Neuromuscular Factors**
Raschner et al.\textsuperscript{50} reported that a multi-factor analysis of measures of muscular strength may be critical for prevention of injury in both male and female youth ski racers.\textsuperscript{50} Furthermore, Zazulak et al.\textsuperscript{51} demonstrated that the ability to control core and trunk motion in reaction to perturbations in collegiate female athletes may predict injury.\textsuperscript{51} Other studies identified that strength deficits of the hip abductors and external rotators relative to body weight were predisposing individuals for injury (OR=1.12).\textsuperscript{52} Specifically in female athletes, decreased hamstring strength is a predisposing factor for injury, when compared to healthy matched control males.\textsuperscript{53} The use of tensiomyography (TMG) (measurement of contractile properties of muscle) in male soccer players revealed a decreased resistance to fatigue of the hamstrings group,\textsuperscript{54} and the potential for imbalance between the hamstrings and quadriceps muscle groups may place individuals at an increased risk for ACL injury.\textsuperscript{54} Furthermore, elite female handball and soccer athletes may be at a higher risk if electromyography muscular pre-activity of their lateral hamstrings are decreased relative to the lateral quadriceps.\textsuperscript{55} Kramer, Denegar, Buckley, and Hertel revealed that decreased iliotibial band flexibility is related to a history of ACL injury,\textsuperscript{45} and may be related to altered lower extremity movement placing an individual at risk.

**Physiologic Factors**
A higher than average weight (RR=1.9)\textsuperscript{12} or BMI (BMI > 19.9 \text{kg/m}^2; \text{RR}=2.0; \text{OR}=2.4)\textsuperscript{12,56} have been reported to place individuals at a higher risk for injury. Furthermore, individuals post menarche (after the onset of menses; \text{OR}=6.68)\textsuperscript{56} or present in the pre-ovulatory menstrual phase (\text{OR}=2.59 to 3.22) are at increased risk.\textsuperscript{21,57-59} Sex has been identified as a risk factor, though with conflicting evidence.\textsuperscript{24,28} Fernandez-Jaen et al.\textsuperscript{28} revealed, ACL tears (mechanism unreported) occur more frequently in males (\text{OR}=2.217; at least 18 years old; adjusted for age), while Beynnon et al.\textsuperscript{24} found, females are at a greater risk for first-time non-contact ACL injury (\text{RR}=2.1; adjusting for sport and level of play). Finally, individuals who are younger than 14 years are at an increased risk for injury to their ACL.\textsuperscript{56}

**Biomechanical Factors**
Individuals who present with the following biomechanical characteristics have been demonstrated to be at altered risk for ACL injury. Knee valgus on landing results in increased ground reaction forces,\textsuperscript{60} placing females at an increased risk of injury.\textsuperscript{61,62} Furthermore, Quatman et al. reported that relative to normal landing,\textsuperscript{61} various combinations of tibial movement (e.g. anterior translation + abduction, anterior translation + external rotation, etc.) resulted in an increased strain on the ACL, with combined abduction and anterior tibial translation showing the greatest tension on the ACL (4.6 times normal).\textsuperscript{61} Moreover, Tainaka et al.\textsuperscript{63} demonstrated that individuals with an increased amount of hip internal and external rotation during active range of motion relative to body weight are less likely to sustain injury compared to others (ER OR=0.23; IR OR=0.18).\textsuperscript{63}

**Genetic Factors**
Seven studies investigated a potential genetic predisposition for ACL injury. Five identified that the presence of variants of collagen genes (e.g. COL1A1, COL12A1) in both sexes increase the likelihood of injury to the ACL (OR=0.8 to 6.6).\textsuperscript{64-68} One study demonstrated that matrix metalloproteinase genes, which play an important role in tissue remodeling, may have an association with injury.\textsuperscript{69} Finally, one reported the presence or absence of polymorphisms of proteoglycan genes may predispose individuals for ACL injury (OR= 0.33 to 9.231).\textsuperscript{70}

**Other Factors**
The following did not fit within other categories, and were reported as risk factors in the female sex. Individuals with previous ACL injury are at a higher likelihood for injury in the same knee (OR= 9.08),\textsuperscript{71} and individuals with family history of ACL injury (immediate family) are at an increased likelihood of injury (OR= 3.57).\textsuperscript{56,72} When examining female youth soccer players, there was a higher prevalence of ACL injuries in their non-dominant leg.\textsuperscript{56} Furthermore,
female recreational skiers were demonstrated to be at an increased risk of injuring their non-dominant leg compared to their dominant (OR = 2.0).  

DISCUSSION

This systematic review presents a wide view of potential risk factors for ACL injury, which are both intrinsic and extrinsic in nature. The majority of the extrinsic factors identified are related to the effect weather conditions have on participants during specific sport participation or the conditions of the playing surface, which have been reported in prior reviews. Findings presented in this review demonstrate that both sexes may be affected by eroding conditions due to the weather and other external factors. Weather conditions related to an increase in odds of injury for women were those during recreational skiing (icy conditions and during snowfall), while the weather conditions for men were related to dry conditions on the pitch for Australian Football. These findings are presented by sex due to the lack of studies examining these conditions across sexes. Regarding the results of this review, the conditions of ski slopes and the rainfall for field-based participation should be considered.

While there is an abundance of literature identifying intrinsic risk factors, unfortunately the majority of studies included in this review surrounded non-modifiable anatomic factors. Eleven studies reported a decreased intercondylar notch width or notch width index, and 11 others identified an increased lateral or posterior tibial plateau slope as a risk factor. Alentorn-Geli et al. reported both factors, and although they are non-modifiable, suggested that injury risk may be mitigated through the implementation of neuromuscular preventative training programs. Within anatomic risk factors, the studies reviewed have presented conflicting evidence regarding how changes in the morphometric characteristics of the bony ridge (increases/decreases in size) within the intercondylar notch affect an individual’s risk of sustaining ACL injury. Future inquiry is necessary to determine whether the characteristics of this ridge are consequential.

The majority of the neuromuscular and biomechanical risk factors are presented as modifiable. Those that stand out in this review are impairments of core stability, increased knee valgus, and increased knee abduction moment and angle on landing. These risk factors may be addressed through neuromuscular preventative training programs. Decreased resistance to fatigue was a risk factor found only in males. Neuromuscular (e.g. EMG muscular pre-activity) and biomechanical (e.g. increased knee valgus on landing) factors were found predominantly in females. Decreases in strength and range of motion were risk factors present in both sexes. Myer et al. discuss that hamstring strength and hamstring to quadriceps ratio remain relatively unchanged as females mature, which may increase the likelihood of developing neuromuscular imbalances, thus potentially increasing females risk of sustaining ACL injury.

Some physiologic factors seem to be on the non-modifiable end of the spectrum, such as the pre-ovulatory phase of the menstrual cycle, and the onset of menarche. These are viewed as non-modifiable as the individual may not have control over if or when they happen. The final risk factor that showed a high prevalence in the literature review is the potential for a genetic predisposition. There were six separate studies that demonstrated that variants of multiple collagen genes may play a role in the development of future ACL injury in both sexes. Similar to physiologic factors, an individual does not have control over their genetic makeup. However, the individual may take themselves out of participation in order to circumvent the potentially negative affect of some of these factors.

Along with national sports governing bodies (i.e. NCAA, National Federation of State High School Association [NFHS]), colleges/universities and high schools play a crucial role in contributing to safety during sport participation by governing their affiliated teams and through the development of their sports venues. When adjusted for socioeconomic, health, and lifestyle variables, adolescents who participate in organized sport activities at any level more than four times per week are at higher odds of injury (female, male; Hazard Ratio = 8.5, 4.0). This places sport governing bodies in a key role for implementation of preventative strategies focusing on the amount of time per week individuals participate. Managing participation by maintaining adequate...
recovery time may be a strategy for the reduction of this risk factor, as neuromuscular fatigue may lead to a negative change in mechanics (e.g. increased valgus collapse) during landing tasks. On the development and maintenance of sporting venues, the type of grass used on fields has been shown to play a role in risk of ACL injury, specifically for men with Bermuda grass increasing their risk. Furthermore, for those institutions which house ski teams, the maintenance of the slopes may play a role for their conditions. Future research regarding eroding weather conditions and playing surface type should focus on the effects applicable to both sexes in order for more informed decisions to be made by sport governing bodies (i.e. NCAA, NFHS) and universities or high schools for decisions on cancellation of sport activities based on weather and for the development and refurbishing of sporting venues.

Limitations to this systematic review include that this report did not include a synthesis of previous systematic review findings, though attempts to encompass risk for both sexes were made. High risk of bias for included studies is a limitation, however, Table 2 provides clarification as to where the bias in each study may come from. Another limitation includes the search of only two databases for articles. Future directions for research regarding ACL injury include a clarification of conflicting evidence of risk factors and identification of specific methods for alteration of known factors.

CONCLUSION
This systematic review attempts to describe documented risk factors for ACL injury for both sexes to further preventative efforts. While there were a few male specific risk factors, and a number found in both sexes, most of the risk factors identified were present for females. The information presented herein reaffirms that injury to the ACL likely results from a plethora of underlying risk factors. While some of the factors presented in this review may be modified, there are many which an individual may not be able to control or modify. The majority of extrinsic risk factors fall in the non-modifiable category. The nature of sport itself will continue to put those who choose to participate at some level of risk to injury. It may prove beneficial to attempt to change those factors with potential for modification (i.e. field type) as those may provide a widespread reduction of exposure. Further research on modifiable factors may provide insight for the development and advancement of injury prevention programs with the aim to decrease the incidence of injury.

REFERENCES


ABSTRACT

**Background:** The knee joint is one of the most frequently injured regions in the game of golf, and the loads experienced by the knee during the golf swing are typically greater than during other activities of daily living. Altering movement patterns is a common strategy that can be used to reduce loading on the knee joint but has received little attention during studies of the golf swing. The primary aim of this study was to examine the effect altering golf stance has on the lead limb peak external knee adduction moment.

**Study Design:** Laboratory based, quasi-experimental

**Methods:** Twenty healthy participants were recruited for a 3-dimensional biomechanical analysis wherein participants hit three golf shots with a driver using the following stance conditions: self-selected, bilateral 0º foot angle, bilateral 30º foot angle, wide stance width, and narrow stance width.

**Results:** Both the 30º foot angle (0.80 ± 0.51 Nm) and wide stance width (0.89 ± 0.49 Nm) conditions significantly decreased (p < 0.001) the lead limb peak external knee adduction moment compared to the self-selected (1.15 ± 0.58 Nm) golf stance. No significant differences (p = 0.109) in swing speed were found between any of the stance conditions.

**Conclusion:** The externally rotated foot position and wider stance width decreased the lead limb peak external knee adduction moment without hindering swing speed. Modifying stance could be a viable option for golfers who wish to continue playing the sport at a high level, while reducing potentially detrimental loads at the knee joint.

**Levels of Evidence:** 2b-Individual cohort study

**Keywords:** Biomechanics, golf, injury, knee, osteoarthritis
INTRODUCTION
Golf is a popular sport played by roughly 55 million individuals. Considering its perceived low impact nature and aerobic exercise component, golf is widely recommended by medical professionals for patients wishing to remain active in the later stages of life. However, previous research indicates that up to 72% of golfers have experienced an injury, suggesting there is potential for strain on the musculoskeletal system during the golf swing. Specifically, the knee joint is one of the most frequently injured regions. The forces and moments experienced by the body during the golf swing are not believed to be of sufficient magnitude to cause acute injury, but it is possible that chronic abnormal loading may lead to knee injury. Since golf is a popular choice of exercise for many individuals, interventions to reduce potentially harmful loading of the knee may expand the longevity of one's playing career.

The external knee adduction moment has traditionally been used as a surrogate measure of the distribution of forces between the medial and lateral compartments of the knee joint. Previous researchers have shown a strong association between a high peak external knee adduction moment during gait and the presence, progression, and pain of medial compartment knee osteoarthritis (OA). Furthermore, knee joint loading may be of interest to a golfing population since forces have been reported to be substantially larger during the golf swing than various activities of daily living (i.e. walking, stair ascent, and stair decent). Therefore, strategies to reduce the peak external knee adduction moment during the swing may be helpful in terms of lowering the risk of the development or progression of knee OA in golfers.

Altering movement patterns has been used effectively to reduce loading on the knee joint during gait. Specifically, adaptations such as increasing one's self-selected foot angle (internal/external rotation of the foot) or stance width have both been shown to decrease the peak knee adduction moment during gait. Indeed, Lynn et al. reported a reduction in the peak external knee adduction moment when both feet were externally rotated 30º, compared to 0º (feet perpendicular to target line). Considering golfers do not typically stand with a 0º foot angle, comparing the peak knee adduction moment during altered stances in relation to a golfer's self-selected stance may give a more realistic representation of the potential reductions in loading. Also, no researchers have examined the effects of altering stance width on the peak external knee adduction moment during the golf swing. Since a wider stance width has been shown to decrease the knee adduction moment during gait, the strategy may also result in beneficial reductions of the moment during the golf swing.

Although altering stance has been shown to decrease loading at the knee, manipulations to a golfer's stance may have implications on performance. Swing speed is a relatively simple marker of performance since it is strongly correlated with total driving distance. Therefore, when considering alterations to swing technique, it is pertinent to examine whether they have negative implications for swing speed.

In summary, there is limited research exploring strategies to reduce the external knee adduction moment during the golf swing. Therefore, the primary aim of this study was to examine the effect altering golf stance has on the lead limb peak external knee adduction moment. It was hypothesized that increasing foot angle and/or increasing stance width of a golfer's stance would significantly decrease the peak external knee adduction moment. The secondary aim of this study was to examine the effect that the previously mentioned stance alterations have on swing speed.

METHODS
This was a laboratory based, quasi-experimental study design. The independent variables include foot angle (self-selected, 0º, and 30º) and stance width (self-selected, narrow, and wide). The dependent variables were the golfer's lead limb peak external knee adduction moment and swing speed at impact.

All participants had to be between the ages of 18-55 with a USGA golf handicap of 20 or below. Participants were excluded if they: were unable to perform multiple golf swings without pain or injury; had undergone orthopedic surgery; had current or previous injuries that limited golf activity in the prior three months; or exhibited any physical or medical
problems for which exercise would be contraindicated. The study was approved by the University of Kentucky Institutional Review Board and all participants provided informed consent.

The final sample included 20 healthy volunteers, 16 males (age: 26.3 ± 6.5 yrs, height: 1.79 ± 0.07 m, mass: 83.6 ± 10.6 kg, USGA Handicap: 11.6 ± 5.7) and four females (age: 25.3 ± 10.6 yrs, height: 1.65 ± 0.05 m, mass: 60.1 ± 5.4 kg, USGA Handicap: 4.6 ± 9.6). Participants wore a standardized neutral shoe (Nike Xccelerator TR, Beaverton, OR) in their own size for the entire data collection. Using double sided adhesive tape, fifty-seven reflective markers were placed on the participant's skin or shoe over the following anatomical landmarks: bilateral acromion process, sternal notch, spinous process of the seventh cervical vertebrae (C7), spinous process of the twelfth thoracic vertebrae (T12), bilateral iliac crest, bilateral ASIS & PSIS, bilateral greater trochanter, bilateral medial & lateral knee, bilateral medial and lateral malleoli, bilateral lateral heel, bilateral proximal & distal heel, bilateral 1st & 5th metatarsal head, bilateral third toe, and an offset marker on the right foot. Lastly, rigid body clusters of four markers were placed on the anterior/lateral aspect of the subject’s right shank and left thigh/shank, while five markers were used on the right thigh.

Participants were given the option to use one of four drivers for the data collection: left or right men's Callaway X Series (10.5 loft, standard length, and stiff flex shaft) and left or right women's Callaway X Series (10.5 loft, standard length, and ladies flex shaft). Participants were asked to address the golf ball with their normal (self-selected) golf stance while a pen was used to mark the ground next to the heel and third toe of each foot. The investigators then drew a line representing the longitudinal axis of the foot in the transverse plane (this represented the self-selected stance position). This line was subsequently used to create additional markings, enabling the participants to alter their foot angle (while keeping stance width constant) and stance width (while keeping foot angle constant). Stance width was defined as the distance between the centers of the heels. Following a brief warm up period (approximately five minutes of practice swings and drives), participants were asked to hit three golf
MD). Raw marker trajectory data were filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 12 Hz. The cut-off frequency was determined by use of a residual analysis. An X-Y-Z Cardan sequence (sagittal-frontal-transverse) was used to quantify joint angles, in which the distal segment was expressed relative to the proximal segment. An adapted version of the model from Nesbit et al. was utilized for the lower extremity kinematic and kinetic calculations. Discrete variables of interest included the lead limb peak external knee adduction moment. The peak external knee adduction moment was determined by the greatest value observed between the top of the backswing and the finish of the golf swing. Lastly, top of backswing and finish events were used to time normalize data, and an ensemble mean value for three consecutive golf swings was calculated for each subject for each of the five stance conditions.

STATISTICAL METHODS
Repeated measures ANOVA analyses were used to determine if there were differences in the peak external knee adduction moment and swing speed between the stance conditions. A planned contrasts analysis was used to determine which (if any) stance conditions were significantly different from the self-selected condition at an alpha level of p < 0.05. Furthermore, Pearson product-moment correlations were performed to determine if the magnitude of change in the external knee adduction moment was related to how much a participant altered their foot angle or stance width from their self-selected position. Specifically, correlations were performed between: i) the change in foot angle vs. the change in the peak external knee adduction moment between the self-selected and 30° foot angle conditions, ii) the change in stance width vs. the change in the peak external knee adduction moment between the self-selected and wide stance width conditions. All statistical analyses were performed using SPSS 24 statistical software (SPSS Inc., Chicago, IL).

RESULTS
Descriptive statistics for the peak external knee adduction moment and swing speed for all stance conditions are presented in Table 1. The ensemble mean curves of the peak external knee adduction moment are shown in Figure 2, which demonstrates that the peak moment occurred just after impact. On average, the participants addressed the ball with a self-selected foot angle of 11.3 ± 5.3° external rotation and stance width of 0.49 ± 0.07 meters. The peak external knee adduction moment was significantly different (p < .001) between the five stance conditions (Table 1). The planned contrasts analyses revealed both the 30° foot angle and wide stance width conditions significantly decreased the peak external knee adduction moment (p < .001) when compared to self-selected. In contrast, the narrow stance width condition significantly increased (p = .023) the peak external knee adduction moment when compared to self-selected. No significant differences (p = .605) were found in the peak external knee adduction moment between the 0° and self-selected foot angle conditions. Furthermore, a weak correlation was found between the change in foot angle vs. the change in foot angle and stance width conditions significantly decreased the peak external knee adduction moment (p < .001) when compared to self-selected. In contrast, the narrow stance width condition significantly increased (p = .023) the peak external knee adduction moment when compared to self-selected. No significant differences (p = .605) were found in the peak external knee adduction moment between the 0° and self-selected foot angle conditions. Furthermore, a weak correlation was found between the change in foot angle vs. the change in the external knee adduction moment (r = -.228, p = .333) and the change in stance width vs. the change in external knee adduction moment (r = .040, p = .866) (Figure 3). In terms of the secondary aim there were no significant differences (p = .109) in swing speed between any of the stance conditions (Table 1).

DISCUSSION
The primary aim of this study was to examine the effect of altering golf stance on the peak external knee adduction moment. The hypothesis was confirmed in that both the 30° foot angle and wide stance width conditions significantly decreased the peak external knee adduction moment.
conditions significantly decreased (p < .001) the peak external knee adduction moment when compared to the self-selected stance. Moreover, 19 and 18 out of the total 20 golfers reduced their peak external knee adduction moment when altering stance to the 30º foot angle and wide stance width conditions respectively. Although previous literature has also reported a reduction in the peak knee adduction moment when the feet are placed in greater external rotation, the magnitude of the change differed slightly from current findings. Specifically, Lynn et al.12 found a 14.3% reduction in the peak external knee adduction moment when the feet were externally rotated 30º, while the current study found a 30.4% reduction between the 30º and self-selected conditions. One possible explanation for the greater reduction of the knee moment in the present study is that the participants used a driver whereas Lynn et al.12 utilized a 5 iron. Given the expected greater exertion when using a driver, the potential reductions in knee loading with an externally rotated foot position may be greater than previously reported.

To the authors’ knowledge, this is the first study to examine the effect of stance width on the peak external knee adduction moment during the golf swing. However, present findings mirror the trends reported during gait modification studies. Specifically, Favre et al.16 and Fregley et al.17 found 17.1% and 9% reductions in the peak knee adduction moment respectively when participants widened their stance during walking, while the current study results demonstrated a 22.6% reduction between the wide and self-selected stance width conditions. In addition, Favre et al.16 found a 13.7% increase in the peak knee adduction moment in gait when participants utilized a narrow stance width, while present data suggest a 6.9% increase between narrow and self-selected stances during the golf swing. Given the external knee adduction moment is larger during the golf swing in comparison to walking, a 22.6% reduction in the peak external knee adduction

<table>
<thead>
<tr>
<th>Stance Condition</th>
<th>Peak Knee Adduction Moment (Nm/kg)</th>
<th>Swing Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-selected</td>
<td>1.15 (0.90-1.41)</td>
<td>98.87 (94.25-103.48)</td>
</tr>
<tr>
<td>0 degree</td>
<td>1.12 (0.89-1.36)</td>
<td>97.90 (93.33-102.47)</td>
</tr>
<tr>
<td>30 degree</td>
<td>*0.80 (0.58-1.03)</td>
<td>98.30 (93.98-102.62)</td>
</tr>
<tr>
<td>Narrow</td>
<td>*1.23 (0.98-1.48)</td>
<td>97.30 (93.18-101.42)</td>
</tr>
<tr>
<td>Wide</td>
<td>*0.89 (0.67-1.11)</td>
<td>98.53 (93.87-103.20)</td>
</tr>
</tbody>
</table>

*Significantly different from self-selected (p<0.05)

Figure 3. Ensemble mean of frontal plane moments for lead limb knee joint. Percent swing is normalized from “top of backswing” (0%) to “follow through” (100%) events. Vertical dashed line represents “impact”.

Table 1. Mean (95% Confidence Interval) for peak knee adduction moment and swing speed for golf stance conditions.

Figure 4. Relationship between A) change in foot angle vs. the change in the peak knee adduction moment (self-selected vs. 30º foot angle); B) change in stance width vs. the change in the peak knee adduction moment (self-selected vs. wide stance width).
moment during the golf swing would correspond to an even larger reduction in the absolute moment than those reported in walking.

Although the 30° foot angle and wide stance width conditions successfully reduced loading at the knee, the magnitude of the change in the external knee adduction moment seemed unrelated to the amount that individuals altered their stance parameters (foot angle or stance width). For instance, participants in this study addressed the golf ball with a range of self-selected foot angles (1.1-23.5°) and stance widths (0.36-0.64 m), thus requiring individuals to change their foot angles and stance widths to varying extents to achieve the appropriate modification. However, the weak correlations indicated that individuals with a greater change in foot angle or stance width did not necessarily have a greater reduction in loading at the knee. It is possible that the poor relationship may be partially explained by individual differences in anatomical alignment such as knee varus/valgus, tibial torsion or femoral retro/anteverision, which may cause golfers to respond differently to the stance modifications.

Although this study was conducted using healthy individuals, the findings may also have clinical implications for populations who have, or are risk of developing medial compartment knee OA. It has been widely proposed that reducing the external knee adduction moment may in turn reduce loads placed on the medial compartment knee joint.9-12,14 Therefore, reducing the external knee adduction moment has become a common strategy to not only slow the development/progression of medial compartment knee OA, but also alleviate symptoms from the disease.9-12,14 The findings of the present study suggest that adopting an externally rotated foot position or wider stance width can be used to decrease the peak external knee adduction moment in both males and females.

The secondary aim of this study was to analyze the effect altering a golfer’s stance had on performance. Golf performance has been previously broken down into two components; distance and accuracy. For this study, only swing speed was analyzed since it has been strongly associated to total distance.22 Current results found no significant differences in swing speed between the five stance conditions, thus indicating the alterations in stance did not hinder the ability for the golfer to generate maximum swing speed. Furthermore, the authors believe that the previously mentioned stance conditions will not prevent a golfer from hitting the golf ball his or her maximum distance potential. This suggests that the externally rotated foot position and the wider stance were both successful in terms of decreasing the peak external knee adduction moment without hindering performance, by a measure of swing speed.

This study contained a few limitations. Firstly, swing speed was the only variable used to assess performance. Measuring driving accuracy in addition to swing speed may provide a more complete picture as to how altering a golfer’s stance effects performance. Therefore, future researchers should assess both swing speed and accuracy as performance variables. Secondly, all data collections were performed in a laboratory environment. Therefore, results cannot account for external factors such as surface condition (i.e. grass or sand), surface grade, and the interaction between the surface and shoe which all typically vary during a round of golf.
CONCLUSIONS

The results of the present study indicate that an externally rotated foot position or a wider stance width decreased the lead limb peak external knee adduction moment when compared to a self-selected golf stance. The non-significant changes in swing speed between stance conditions suggest the previously mentioned alterations in stance may be used to decrease joint loading without hindering the golfer’s ability to generate maximum swing speed. Therefore, adopting a 30º foot angle or a wider stance width may be viable options for golfers to reduce potentially harmful loads at the knee joint and help them continue playing the sport at a high level. In particular, the findings may have clinical implications for those individuals who are at risk of the development or progression of medial compartment knee osteoarthritis.

REFERENCES

ABSTRACT

Background: The Musculoskeletal Readiness Screening Tool (MRST) was developed in an effort to consistently predict injury among military personnel. Current injury prediction tools have not consistently predicted injury in this population. The MRST is comprised of the weight bearing forward lunge, modified deep squat, closed kinetic chain upper extremity stability test (CKCUEST), forward step down with eyes closed, stationary tuck jump, unilateral wall sit hold, and subjective, individual perceived level of risk for injury. The Feagin hop and self-reported history of injury were also included in this study protocol. The Feagin hop was a functional test used consistently by the orthopedic department located at the testing site as well as used in a recent study aimed at defining a return to duty screen; self-reported history of injury has been identified as a potential predictor of injury.

Purpose: To examine whether MRST scores, as a composite as individual components, were predictive of a United States Military Academy Preparatory School (USMAPS) student athlete sustaining a future musculoskeletal injury.

Study Design: Prospective Cohort Study

Methods: MRST scores were collected for 141 student athletes (mean age 18.63 ± 1.31) at USMAPS. The injury surveillance period was nine months. Students participated in regularly occurring military specific training and various sports. Mean scores were compared between injured and uninjured groups; binary logistic regression model was also completed.

Results: Seventy students sustained an injury. The top activities resulting in injury included football (36%) and basketball (11%) with injuries predominantly located in the lower extremity including the knee (24%), hip (15%), and ankle (14%). Composite MRST scores were not statistically different between injured (12.58 ± 2.16) and uninjured (13 ± 2.27) groups. There was an association between those with a personal concern for future injury and actual injury (p = .04). There was an association between those reporting a prior injury in the preceding 12 months and those incurring an injury at USMAPS (p = .04).

Conclusion: The MRST composite scores were not predictive of injury in this population. Previous injury and personal concern for injury were significant injury predictors.

Level of Evidence: 2a

Key Words: Fear of injury, injury prediction, military, previous injury

Acknowledgements: The research team would like to extend our sincere gratitude to USMAPS, Robby Vought, MS, ATC, Timothy Hansen, MS, ATC, Erin Miller, LAT, ATC, Michael R. Johnson, PT, DSc, John S. Mason, PT, DSc, Jeffery Dolbeer, PT, DSc, Traci Dolbeer, PA, Jamie Morris, PT, DSc.
INTRODUCTION
Musculoskeletal injuries pose the greatest threat to military readiness during both peacetime and combat operations, especially with the U.S. military drawdown of recent years. Many of the musculoskeletal injuries are sustained as a direct result of participation in sports and physical training. Injuries observed in military service are consistent with those incurred by professional athletes and the subsequent demands put on the military healthcare system are tremendous. In the active component of the U.S. Armed Forces, there were 3.6 million injury related encounters in 2014 alone. Physical training is conducted regularly across the military population. For females, physical training represented the most common cause of musculoskeletal injuries. For males, physical training was closely followed by basketball, football, and softball as the most commonly reported cause of such injuries. Prevention of these sports and physical training injuries is a top priority for leaders in the Department of Defense. Currently, there is literature aimed at identifying physical and mental (actual and perceived) factors that may predict future injury. For example, prior injury, impaired strength and neuromuscular control are associated with increased risk for second injury after anterior cruciate ligament restriction in athletes. However, no existing standard physical performance exam can consistently predict future injury for various athletes and occupations. As a result, sports health professionals and military clinicians treating previously injured athletes are left to use time-based protocols and expert opinion to guide their decision making process.

While individual physical performance measures have been positively associated with injury prediction, evidence also exists that a combination of functional tests, such as the FMS, may predict future injury. However, the isolated use of the FMS to screen for injury risk is not recommended because of the low predictive value and misclassification of injury risk. Combining physical performance tests with at least moderate predictive validity for musculoskeletal injury with a basic military task analysis, a team of military physical therapists developed a return to duty screening tool consisting of six specific functional movements and one subjective question called the Musculoskeletal Readiness Screening Tool (MRST). The authors of one study found that the MRST showed potential as a tool for identifying service members at risk for injury. The original idea behind this injury prediction tool came from an author who designed a return to duty screen with good inter-rater reliability. The purpose of this study was to examine whether MRST scores, as a composite as individual components, were predictive of a United States Military Academy Preparatory School (USMAPS) student athlete sustaining a future musculoskeletal injury. Investigators hypothesized that subjects with a lower MRST composite score would have a greater likelihood of sustaining a musculoskeletal injury.

METHODS
Study design and subjects.
This was a prospective cohort study approved by the Institutional Review Board at Keller Army Community Hospital. Two hundred thirty-seven student athletes were briefed during the first week of attendance regarding the study, including procedures, benefits, and risks. One hundred forty-one participants volunteered (mean age 18.63 years ± 1.31). Enrollment and data collection occurred over the course of three days. Participants provided written informed consent and Health Insurance Portability and Accountability Act authorization, permitting the use of protected health information for research. Two days prior to initial data collection, all investigators completed two hours of preparatory training. For each day of data collection, the research team...
Musculoskeletal Readiness Screening Tool

The MRST is a screening tool composed of six functional movements and a question regarding perceived risk of future injury. (Figure 2) For the purposes of this study, an additional physical performance measure and one question regarding the subject’s prior musculoskeletal injury history were also collected. The Feagin hop was a functional test used consistently by the orthopedic department located at the testing site as well as used in a recent study aimed at defining a return to duty screen; self-reported history of injury has been identified as a potential predictor of injury.
Tests were scored on a 0-2 ordinal scale. A score of 2 indicated the subject was able to perform the movement according to prescribed criteria and without pain. A score of 1 indicated that only part of the movement was complete and the subject performed the movement without pain. A score of 0 indicated that the subject had pain with the movement or had a bilateral deficiency on the weight-bearing lunge forward lunge. The individual prior injury component was scored on a 0-1 ordinal scale. A score of 1 indicated no prior injury whereas a score of 0 indicated prior injury. For personal concern of future injury, a score of 2 indicated no concern, a score of 1 indicated mild to moderate concern, and a score of 0 indicated significant concern for injury. The total score ranges from a minimum of 0 points to a maximum of 17 points (2 points per physical test, 2 points possible for no personal concern for injury, and 1 point for no prior injury).

**Weight Bearing Forward Lunge**
The weight bearing forward lunge test was performed with shoes off. Participants assumed a shoulder-width staggered stance position with two fingers touching the wall, as a balance aid only, and the tip of the forward great toe 12cm from the wall. The subject lunged forward while attempting to keep the front heel on the ground. This was repeated for the contralateral limb. The participant received 2 points if each of the patellae contacted the wall and the great toe was positioned 12cm or greater away from the wall. One point was awarded for unilateral achievement, and 0 points if the test was painful or the subject was unable to touch the wall bilaterally. Measurement of weight bearing dorsiflexion has been found to be reliable for novice and expert testers. In previous studies, the ankle dorsiflexion lunge was a reliable predictor of injury.

**Modified Deep Squat**
The modified deep squat was initiated with the participant standing barefoot and the shoulders abducted 180 degrees and elbows extended to 90 degrees. With the toes facing directly forward, the subject attempted to squat low enough for the thighs to break parallel with the floor. Two points were received for an upper torso that remained parallel with the tibia or vertical, arms in line with the torso, femur below horizontal, and the knees aligned over the feet. Failure to meet any of the criteria listed resulted in one point, and 0 points if the test was painful. The deep squat has been validated as part of the Functional Movement Screen.

**Closed Kinetic Chain Upper Extremity Stability Test (CKCUEST)**
The CKCUEST required the subject to assume a push-up position with the shoes on. Males started in the push-up position and females began in the kneeling push-up position. With the back slightly inclined in relation to the floor and the hands 36 inches apart, the subject leaned over to touch one hand on the other and then returned the hand to the starting position. Tape marked the starting position for each hand and a folded towel was placed under the knees for comfort of female subjects only. This procedure was repeated in a rapid alternating fashion and 2 points were awarded for 20 repetitions, 1 point for less than 20 repetitions, and 0 points awarded if the test was painful regardless of the number of repetitions completed. The CKCUEST has a high test-retest reliability and inter-rater reliability is excellent. This test is significantly correlated with both left and right side injuries. It has a sensitivity of 0.83, a specificity of 0.79, and odds ratio of 18.75 in determining a shoulder injury using a score of 21 touches.

**Forward Step Down**
The forward step down with eyes closed began with the shod subject standing on a standard 8-inch step with the feet approximately shoulder width apart. The subject held two hardcover textbooks weighing approximately 6.8 kilograms at navel level with elbows flexed to 90 degrees and eyes closed. The textbooks were not permitted to make contact with the subject anywhere other than the hands. The subject stepped down with one leg at a time while the investigator stood in front of the subject for safety. Two points were awarded if the subject kept the eyes closed and there was no deviation of the lower extremities in the frontal plane. One point was awarded if the eyes opened, a loud foot landing determined subjectively by tester, or any frontal plane deviation was noted. Finally, 0 points were awarded if the test was painful.
Stationary Tuck Jump
The stationary tuck jump involved the subject standing with feet shoulder width apart, arms at the side in an athletic crouched position. The subject initiated a jump with arms extended behind the subject and while swinging the arms forward the subject jumped vertically, pulled the knees up as high as possible and then attempted to land softly in the same position. This was repeated quickly three times such that each jump occurred immediately upon landing from the preceding jump. If the subject could perform three jumps with thighs at least oriented 45 degrees in the sagittal plane about a coronal axis, landing in approximately the same position with a soft landing 2 points were awarded. One point was awarded if the subject did not meet the criteria, and 0 points awarded if the test was painful.19,20 It also has good intra-tester and inter-rater reliability in its typical performance over 10 seconds.21

Unilateral Wall Sit Hold
The unilateral wall sit hold required the subject to stand with body weight evenly distributed, feet shoulder width apart, and shoes on. The back was pressed against the wall with the hips and knees flexed to create an angle between the wall and thigh at 45 degrees. The arms hung vertically and then the subject lifted one foot such that it was 1-2 inches off the floor. The investigator started the stopwatch and then stopped at 30 seconds or when the athlete could not sustain the test position. One minute of rest was followed by testing of the contralateral limb. Two points were awarded for maintaining the test position for 30 seconds bilaterally. Only 1 point was awarded for holding less than 30 seconds on either extremity and 0 points awarded if the test was painful. The unilateral wall sit hold is a significant predictor of injury for NCAA football.22

Feagin Hop
The Feagin hop test involved the subject standing directly on a line with the non-test lower extremity held in slight knee flexion with the shoes on. The subject performed a maximum effort vertical hop. This was performed twice on each leg. Two points were awarded for landing in the same position with a soft landing and no frontal plane deviation bilateral. Only 1 point was awarded if the subject did not meet all criteria above and 0 points awarded if the test was painful.14 The Feagin hop test was included in a military return-to-duty screen and found to have moderate to good interrater reliability.14

Questionnaire
Participants completed a questionnaire to assess their history of previous injury and other descriptive information. The first question asked, “Have you experienced a prior injury that limited your participation in athletics or daily activity for more than seven days within the last 12 months?” Response categories were “yes” or “no”. One point was awarded for the answer no and 0 points awarded for answering yes. The follow-up questions asked, “If you answered yes for question #1, please identify the following from your prior injury by circling the words that best fit your injury.” “Was the injury on your left or right?” “The injured body part was head, arm, leg, back, or chest/torso?” “The injury occurred during contact or non-contact sport?” Next, the subject’s personal concern for injury was asked ensuring the participant circled only one answer: “How would you describe your personal concern for sustaining a musculoskeletal injury within the next nine months?” Responses included, “no concern for injury, mild to moderate concern for injury, or significant concern for injury.” Two points were awarded for no concern for injury. One point was awarded for mild to moderate concern for injury and 0 points awarded for significant concern for injury. Age in years, height in inches, weight in pounds, and gender were also collected. Finally, the following demographic data were also collected ensuring participants circled one answer: “Arab, Asian/Pacific Islander, Black, Caucasian/White, Hispanic, Multiracial, and Other.”

Documentation
All health-related records were stored in three primary locations including the paper-based local athletic training record, and two automated medical documentation systems: the Cadet Illness and Injury Tracking System and the Armed Forces Health Longitudinal Technology Application. All medical
encounters were reviewed initially by the principal investigator. In a separate meeting, two USMAPS certified athletic trainers and principal investigator collected all injury documentation occurring from August 2014 through May 2015. Similar to the study by Garrison et al. investigating injury prediction,\textsuperscript{23} injury was defined as an event that resulted in physical impact to the body during the academic school year, the injury required the subject to seek medical care from an athletic trainer, physician, or physical therapist, and the injury resulted in modification of activity for a minimum of 24 hours. The following details regarding each injury occurrence were recorded: contact or non-contact mechanism, traumatic or atraumatic, exact anatomic location(s), diagnosis, activity or sport mechanism of injury, and finally the number of lost duty days.

**Statistical Methods**

Mean MRST scores were compared between injured and uninjured groups with an independent t-test. With nine predictors, investigators sought a minimum of 15 subjects per predictive test or 135 subjects to conservatively ensure adequate power. All MRST composite scores were evaluated to see if any score would be associated with the greatest degree of both sensitivity and specificity. Several elements of the data were analyzed including total MRST score, history of past injury, and a personal concern of injury. Odds ratios, sensitivity, specificity, and likelihood ratios were calculated for each of these conditions. To determine if the MRST could predict future injury, logistic regression models were performed. Predictor variables were determined by analyzing individual component scores on the MRST, the composite MRST score, past history of injury, and personal concern for injury. The Pearson's Chi-Square test was used to determine the impact prior injury and personal concern for injury had on future injury. Data analysis was performed using the PEDro Confidence Interval Calculator and the R Core Team 2015 v 3.1.1. (R Foundation; Vienna, Austria).

**RESULTS**

One hundred thirty-three participants (133/141 = 94\%) were included in the final data analysis. Eight participants were lost to follow-up because they left the academy for personal reasons. Mean age was 18.63 years (±1.31), mass 81.04 kg (±16.98), and height 177.46 cm (±10.21). One hundred ten (83\%) of the subjects were male. Forty-one percent of the subjects were self-reported Caucasian/white, 38\% black, and 12\% multiracial. 53\% of participants sustained an injury and 47\% did not sustain an injury during the nine-month 2014-2015 academic school year. The top four activities resulting in injury were: football (36\%), basketball (11\%), free time (11\%), and track (10\%). (Figure 3) Injuries predominantly occurred at the knee (24\%), hip (15\%), and ankle (14\%). (Figure 4)
The mean MRST composite score for the injured group was 12.58 (±2.16) and for the uninjured group was 13(±2.27). Comparing these means with an independent t-test resulted in no statistically significant difference between the two groups (p = .78) No statistically significant difference was observed between composite MRST scores for those that incurred an overuse injury at 12.54 to those uninjured or incurred an acute injury at 12.64 (p = .85).

The impact of prior injury and personal concern for injury had on future injury was also investigated. Using the Pearson’s Chi-Square Test there was a significant association between those reporting a prior injury and those incurring a future injury (p = .04). (Table 1) There was also a significant association between those with a personal concern for future injury and those actually incurring a future injury (p = .04). (Table 2)

Sensitivity, specificity, and likelihood ratios were calculated based on individual MRST components. Of note, the two tests with the greatest sensitivity were the dorsiflexion lunge and squat at 0.62 and 0.85, respectively. The two tests with the greatest specificity were the wall sit hold and CKCUEST at 0.83 and 0.70 respectively. (Table 3)

Odds ratios compared the predictive power of the MRST composite scores and prior injury. No MRST composite score was identified as a useful cutoff score for predicting future injury. The composite score that represented the best combination of sensitivity and specificity was 12 with an odds ratio of 1.33 (0.67, 2.64).

**DISCUSSION**

Results indicated that MRST scores were not predictive of injury in USMAPS student athletes. A previous history of injury was predictive of future injury. A USMAPS student athlete that reported a previous injury had an 83% chance of sustaining an injury.

### Table 1. Association Between Self-Reported Prior Injury and Nine-Month Injury Follow-Up.

<table>
<thead>
<tr>
<th></th>
<th>Uninjured</th>
<th>Injured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior Injury</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>No Prior Injury</td>
<td>52</td>
<td>47</td>
</tr>
<tr>
<td>p = 0.04. Odds Ratio: 2.3; 95% CI (1.02, 5.25)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Association Between Self-Reported Concern For Injury and Nine-Month Injury Follow-Up.

<table>
<thead>
<tr>
<th></th>
<th>Uninjured</th>
<th>Injured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concern</td>
<td>23</td>
<td>38</td>
</tr>
<tr>
<td>No Concern</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>p = 0.04. Odds Ratio: 2.1; 95% CI (1.03, 4.14)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Association between Individual Physical Measures on MRST and Injury.

<table>
<thead>
<tr>
<th>Test</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Positive Likelihood Ratio</th>
<th>Negative Likelihood Ratio</th>
<th>Odds Ratio (Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Bearing</td>
<td>0.62</td>
<td>0.44</td>
<td>1.11</td>
<td>0.86</td>
<td>1.29 (0.65, 2.59)</td>
</tr>
<tr>
<td>Forward Lunge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Deep</td>
<td>0.85</td>
<td>0.23</td>
<td>1.10</td>
<td>0.66</td>
<td>1.65 (0.68, 3.96)</td>
</tr>
<tr>
<td>Squat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary Tuck</td>
<td>0.39</td>
<td>0.60</td>
<td>0.98</td>
<td>1.01</td>
<td>0.97 (0.48, 1.97)</td>
</tr>
<tr>
<td>Jump</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CKCUEST</td>
<td>0.09</td>
<td>0.70</td>
<td>0.33</td>
<td>1.28</td>
<td>0.25 (0.09, 0.66)</td>
</tr>
<tr>
<td>Forward Step</td>
<td>0.19</td>
<td>0.67</td>
<td>0.59</td>
<td>1.19</td>
<td>0.49 (0.22, 1.09)</td>
</tr>
<tr>
<td>Down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feagin Hop</td>
<td>0.58</td>
<td>0.45</td>
<td>1.06</td>
<td>0.92</td>
<td>1.14 (0.57, 2.28)</td>
</tr>
<tr>
<td>Unilateral Wall</td>
<td>0.22</td>
<td>0.83</td>
<td>1.37</td>
<td>0.92</td>
<td>1.48 (0.61, 3.56)</td>
</tr>
<tr>
<td>Sit Hold</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRST= Musculoskeletal Readiness Screening Tool, CKCUEST= Closed kinetic Chain Upper Extremity Stability Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Injury. These results are consistent with the results of multiple studies demonstrating that a history of previous injury is the strongest individual predictor of future injury.24–27 The odds ratio of 2.31 for prior injury demonstrates that a student athlete with a history of a prior injury in the previous 12 months has more than two times greater chance of injury than a student athlete without a prior injury.

In this student population, 53% of injuries resulted from sports and physical training, which is consistent with multiple military studies. Musculoskeletal injuries represented the leading cause of medical care visits across the military.3 Physical training and sports are the main cause of non-battle injuries, 56% a direct result of physical training.2 Basketball, football, and softball were the most common sports associated with injury in recent studies examining Air Force and Army sports and physical training injuries. The results of this study are similar, with football, basketball, and free time ranking as the most common activities associated with injury at 36%, 11%, and 11%, respectively. Also similar to Lauder and colleagues,2 the top injuries directly involved the lower extremity with the knee being the most common site of injury.

In this current population, fear of injury was an injury predictor. Previous investigators have observed that psychological factors and the fear of re-injury influence return to play and injury risk.26–30 There appears to be a strong positive correlation of injury occurrence with athletes undergoing greater degrees of stress, whereas athletes with increased optimism toward their activity were less likely to sustain an injury.30 Self-confidence and psychological influences affect sport injury risk.31,32

Although the MRST did not predict injury in this population, it may be useful in predicting injury outside of a student athlete population. Various units in the military participate in more diverse physical activity, such as military training events, without the daily sport activity frequently encountered in a preparatory school. Evaluating the predictive abilities of the MRST in specific military units will help determine its utility in the military.

This study has some limitations that should be taken into consideration. First, exposure to sports was not controlled. Understanding the exposure to training and the participants’ prior fitness levels may help account for the amount of risk the subjects were exposed to and allow for a more accurate comparison of exposure to other studies. This sample consisted of 60% football players which may have affected the injury rate. This was a fairly homogeneous sample and may not be representative of other young, collegiate athletes or the military in general. Finally, there is a lack of reliability data on the Feagin Hop as opposed to the other physical measures identified in this study. This does not mean that the Feagin Hop shouldn't be used; rather, research should be performed to examine it's as an evidence-based test.

The results of this study may provide valuable information to clinicians. It is clear that a prior history of injury and concern for injury continue to be a strong risk factor for injury. Although the MRST did not predict injury, this study provided information on the incidence of injury, sports most commonly associated with injury, and the incidence of injury according to body location in this select population. More research is needed to determine if the MRST should be used with other military personnel or student athletes. This study adds to the descriptive epidemiological research demonstrating lower extremity injuries and sports such as football and basketball account for the most injuries.

CONCLUSIONS

This study contributes to the current research investigating functional movement and screening tools used to predict future injury and suggests injury prediction is likely multi-factorial and may not come down to purely physical or psychological factors alone. Given that the only factors directly associated with injury in this study were reported previous injury and fear of injury, clinicians should continue to query athletes regarding their injury history. Future research should focus on evaluating the reliability, predictive and convergent validity of the MRST, or another screening tool, if it is to potentially be considered a viable option for injury prevention within the military.

REFERENCES

1. Cameron KL, Owens BD. The burden and management of sports-related musculoskeletal


ABSTRACT

Background: Rugby union is a collision sport which is associated with a high injury rate and therefore the development of effective injury prevention strategies is required.

Purpose: This study aimed to determine whether the Functional Movement Screen™ (FMS™) components can predict injury in female and male rugby union players and whether differences exist in the FMS™ scores of injured and non-injured players.

Study Design: Prospective cohort study.

Methods: Sixty-four female university rugby union players (age: 20.39 ± 1.91 years) and 55 male university rugby union players (age: 21.05 ± 1.35 years) completed the FMS™ which assesses seven functional movements on a scale of 0 to 3 and provides a total or composite score out of 21. Players were subsequently monitored for injury during the season and injury rates calculated.

Results: The training injury rates for females were 5.80 injuries/1000 hours and males 5.34 injuries/1000 hours while the match injury rates for females was 55.56 injuries/1000 hours and males 46.30 injuries/1000 hours. FMS™ composite score demonstrated a significant difference between injured females and non-injured males (p = 0.01) and a combined sample comparison of injured and non-injured subjects was significant (p = 0.01). FMS™ composite score was not a good predictor of injury however as FMS™ individual components predicted 37.4% of the variance in total days injured in females. ROC curve analysis revealed an injury cut off score of 11.5 for females and males and provided a sensitivity and specificity of 0.90 and 0.86 and 0.88 and 1.00 respectively. The combined sample FMS™ composite score of ‘multiple injuries’ participants demonstrated no significant difference between non-injured (p = 0.31) and single injury subjects (p = 0.76).

Conclusion: Injury rates between female rugby and male rugby were similar with match injury rates higher in females. The FMS™ can be used to identify those players with the potential to develop injury and the FMS™ injury cut off point was 11.5 for both female rugby and male rugby players. Individual components of the FMS™ are a better predictor of injury than FMS™ composite score.

Key words: Female, Functional Movement Screen™, injury, male, rugby union

Levels of Evidence: 2b.

CORRESPONDING AUTHOR

Ross Armstrong
Department of Sport and Physical Activity
Edge Hill University
St Helens Road, Ormskirk, Lancashire, L39 4QP, United Kingdom.
E-mail: armsross@edgehill.ac.uk
Telephone: (0044) 01695 584246
Fax: (0044) 01695 579997

1 Sports Injuries Research Group, Department of Sport and Physical Activity, Edge Hill University, United Kingdom.

Conflict of interest
The authors report no conflicts of interest.
INTRODUCTION

Rugby union is a collision sport which involves physical contact in scrums, rucks, mauls, line outs and tackling and repeated short duration high intensity workloads which contribute to one of the highest reported sporting injury rates. Within collegiate rugby, match and training injury rates of 99.5 injuries and 5.1 injuries per 1000 hours have been recorded respectively.

The Functional Movement Screen (FMS™) has been used to predict injury across a variety of sports including female collegiate athletes and football based on the suggestion that strength, movement flexibility and stability are required for optimal performance. The FMS™ is a screening tool that consists of seven movements that are graded to identify deviation from normal movement patterns via visual analysis by the tester. The movements are deep squat (DS), hurdle step (HS), in-line lunge (ILL), shoulder mobility (SM), active straight leg raise (ASLR), trunk stability push up (PU) and rotary stability (RS) which are scored from 0 to 3 on each movement providing a maximum score of 21. The FMS™ has good inter-rater reliability (Intraclass Correlation Coefficients (ICC) 0.89) and scientific evidence exists for the use of the FMS™ as a predictor of injury risk.

Injury risk is multifactorial and attempts have been made to create injury risk algorithms for collegiate athletes using field expedient tests (Lower Quarter Y-Balance Test and FMS™) and historical factors (previous injury history and current medical restriction) to categorize injury risk. It was concluded that these field expedient tests in combination with demographic information may help categorize injury risk however the definition of injury used meant that these findings were most applicable to musculoskeletal injuries of non-contact mechanism. In US Army Rangers a combination of predictors were investigated and musculoskeletal injury history, pain provocation on FMS™ clearing tests, movement tests and lower scores on physical performance measures were associated with increased risk of injury. The summation of risk factors produced a sensitive model (one or less factor) and a specific (three or more factors model) for identifying injury risk.

The implementation of injury prevention strategies may potentially reduce the high injury rate reported in rugby. Within female rugby there are limited injury studies at university level and neither utilized movement screening. To the best of the authors’ knowledge no studies exist that have investigated FMS™ as a predictive tool of injury in female university rugby players (FR) and male university rugby players (MR). The primary aim of the study was to determine whether FMS™ composite score and FMS™ individual components can predict injury occurrence in FR and MR. The secondary aim was to report injury demographics in FR and MR and whether differences exist in the FMS™ composite scores of injured and non-injured players. The tertiary aim was to consider the FMS™ composite score of subjects who suffered ‘multiple injuries’ in comparison to non-injured and single injury subjects. The final aim was to consider the role of contusion injuries.

METHODS

Subjects

One hundred and nineteen subjects volunteered to participate in this study (64 FR: age: 20.39 ± 1.91 years, height: 166.5 ± 10.55 cm, mass: 73.98 ± 21.03 kg, 55 MR: age: 21.05 ± 1.35 years, height: 181 ± 6.26 cm, mass: 86.60 ± 14.01 kg). Subjects were recruited at the relevant team training session if they were 18 years of age or older; currently a member of the university rugby union team and attending training and playing matches on a weekly basis. Subjects were excluded from the study if they had suffered an injury in the previous 30 days which prevented them participating in or completing a training session or match. Subjects completed a medical screening questionnaire prior to participating in the study and those who had heart disease and/or were pregnant were excluded from the study. Subjects who scored 0 on any FMS™ movements were excluded from the study. Participation was voluntary and all subjects completed informed consent forms and were provided with an information sheet prior to commencing the study and a debrief sheet following participation. The University Research Ethics Committee provided ethical approval prior to commencing the study in accordance with the Helsinki declaration.

Procedures

Prior to testing, the subjects height (cm) was measured using a stadiometer (Leicester Height Measure,
Child Growth Foundation, Leicester, UK) and body mass (kg) was recorded using digital scales (Salter 9028, Kent, UK) and the subjects date of birth was recorded. Subjects were asked to eat their normal pre-training meal, avoid performance enhancing energy drinks, supplements and strenuous exercise in the 48 hours before testing to reduce fatigue effects and all testing was conducted at 17.00 hours. The researcher was a Musculoskeletal Physiotherapist with 16 years of experience and an MSc in Sports Medicine who was trained in using the FMS™ via attendance at a Functional Movement Screening course.

**FMS™**

Subjects performed the seven movements of the FMS™ which were demonstrated by the researcher who also provided FMS™ images to support correct movement patterns. Verbal instruction was provided to the participants in accordance with guidelines previously reported by Cook et al. Subjects performed each movement three times with a five-second rest between each movement and a one minute rest between each component of the FMS™. The highest score on the three trials were recorded by the lead researcher and subjects returned to their initial standing position between trials. Clearing tests were performed for SM, PU and RS to determine if any subjects had pain that would make performance of these tests unsafe. Performance was assessed on a scale of 0 to 3 based on the following criteria: 0 = Subject experienced pain during movement, 1 = Subject failed to complete the functional movement, 2 = Subject performed using compensatory movement, and 3 = Subject performed the test to perfection. For bilateral movements the lowest score in that FMS™ component was used for analysis and calculation of composite score. No subjects scored 0 on any FMS™ movement and therefore all subjects were pain free. The Intra-rater reliability (ICC 3,1) of FMS™ composite score was assessed by the lead researcher who measured the FMS™ scores of 20 subjects (10 male, 10 female) on two separate occasions 24 hours apart to allow calculation of test-retest reliability. ICC’s were calculated to assess intra-rater reliability and FMS™ composite score had an ICC of 0.99 (95% Confidence Intervals (CI) 0.97 – 0.99) which demonstrated excellent intra-rater reliability.

**Injury definition and playing exposure recording**

Injury was categorized using a time loss definition of injury that defined injury as an event that prevented the player from taking full part in rugby training or matches. Absence was recorded as Total Days Injured (TDI) using Injury Recording Cards and recorded prospectively. Players who were unable to participate in training or matches following an injury were assessed by the researcher and had their injury classified via differential diagnosis as either sprain, strain, contusion, fracture, dislocation, overuse injury or other. The following information was recorded: (1) Injury location. (2) Classification of injury type. (3) Mechanism of injury: (a) Contact injuries resulting from physical contact with a player or equipment (e.g. rugby post) (b) Non-contact injuries. (4) Injury severity: Was graded as slight (0-1 days), minimal (2-3 days), mild (4-7 days), moderate (8-28 days) and severe (greater than 28 days). Players were defined as having recovered from injury once they had been assessed by the researcher and allowed to return to full contact training which included all the physical demands of rugby (e.g. scrums, rucks, mauls, line outs, tackling) or when they started a match. This individual assessment of injury status involved fitness tests of physical demands that would occur in rugby (e.g. sprinting, cutting, tackling, jumping) and appropriate musculoskeletal assessment via joint and muscle testing. Absence due to illness was not recorded to ensure only injury status was investigated. Reinjury was classified as injury of the same type occurring at the same location and the term ‘multiple injuries’ was used for those subjects who suffered more than one injury during the study and did not include reinjuries. Training and match exposure (minutes) was recorded by the researcher using a playing and training time attendance register and results are reported as (mean ± SD). Injury rates calculated as injury/1000 hours training and match exposure.

**Statistical analysis**

All analysis was performed using the combined sample and further analysed for both males and females and separately. For regression analysis a Durbin-Watson test was used to assess independence of
observations and a scatterplot was used to assess linearity between FMS™ variables and TDI. Case wise diagnostics were used to check for outliers. The assumption of homoscedasticity was checked by inspection of a plot of the unstandardized values against predicted values. Normal probability-probability (P-P) plots were used to assess normal distribution and ensure that the variance in residuals were constant. Cohen's $d$ was used to assess effect size for all regression analysis. Linear regression, multiple linear regression and stepwise multiple hierarchical linear regression analysis was used to quantify the effect of FMS™ composite and FMS™ individual components scores as a predictor of TDI. Linear regression analysis was used to quantify the Pearson correlation coefficient ($r$) between FMS™ composite score and TDI. Multiple linear regression was subsequently used to correlate TDI with each of the independent FMS™ components. This approach quantifies TDI as a function of the discrete elements. Stepwise multiple hierarchical linear regression was used to establish a hierarchical ordering for those FMS™ components which most influence TDI. This technique used the seven FMS™ components with the highest $r$ entered in pairs into the model commencing with the element with the highest $r$ value. All assumptions were met for all regression analysis. To consider the role of contusion injuries and the possibility they may potentially occur due to chance, all forms of regression analysis were repeated with contusion injuries removed from analysis.

Quantile-quantile (Q-Q) plots were observed and the groups were observed to be normally distributed. For one-way Anova analysis of FMS™ composite scores in injured FR, non-injured FR, injured MR and non-injured MR there was homogeneity of variances as assessed by Levene's test for equality of variances ($p = 0.40$). A post-hoc Tukey test was used to analyse differences between groups and a partial eta squared squared ($\eta^2$) calculation provided effect size. An independent t-test was used to analyse FMS™ composite score in injured and non-injured subjects. Q-Q plots were observed and the groups were observed to be normally distributed. There was homogeneity of variances as assessed by Levene's test for equality of variances for all three comparisons (combined, $p = 0.76$, FR, $p = 0.61$, MR, $p = 0.18$). This analysis of injured and non-injured subjects included all injuries recorded and a separate analysis was performed with contusion injuries removed and homogeneity of variance existed for all three comparisons (combined, $p = 0.96$, FR, $p = 0.39$, MR, $p = 0.29$). An independent t-test was used to assess FMS™ composite score between 'multiple injuries' subjects and those who had suffered no injury or one injury. Due to the low numbers of subjects classified as 'multiple injuries', meaningful statistical analysis was only possible between combined sample and non-injured subjects and combined sample and single injury subjects. Homogeneity of variance existed for both comparisons with values of ($p = 0.63$ and $p = 0.57$) respectively. A separate analysis was performed with contusion injuries removed and homogeneity of variance existed for 'multiple injuries' subjects and non-injured subjects ($p = 0.71$) and 'multiple injuries' and single injury subjects ($p = 0.62$). Receiver operator characteristic (ROC) curves were produced to assess the predictive ability of the FMS™ composite scores and FMS™ components between injured and non-injured subjects to determine the cut-off score for sensitivity and specificity as a predictor of injury.

RESULTS

Regression analysis

Table 1 reports linear regression analysis of FMS™ composite score as a predictor of TDI for all injuries. FMS™ composite score was a significant predictor for combined sample ($p = 0.04$) and FR ($p = 0.03$). The best FMS™ component predictor was FR LIL ($r^2 = 0.12$, Durbin Watson 2.23, $p = 0.01$, $F = 8.23$). FMS™ composite score had a small Cohen's $d$ effect size for combined sample (.19), MR (.20) and FR (.27) in relation to TDI.

Analysis with contusions removed revealed no differences in statistical outcome. FMS™ composite
score was a significant predictor for combined sample ($r^2 .04$, Durbin Watson 2.192, $p = 0.04$, $F = 4.29$, Cohen’s $d .20$). FMS™ composite score was a significant predictor of FR TDI ($R^2 .07$, Durbin Watson 2.085, $p = 0.04$, $F = 4.06$, Cohen’s $d .26$). FMS™ composite score was not a significant predictor for MR TDI ($r^2 .04$, Durbin Watson 2.386, $p = 0.14$, $F = 2.21$, Cohen’s $d .20$). The best FMS™ component predictor remained FR LIL ($r^2 .13$, Durbin Watson 2.05, $p = 0.01$, $F = 7.87$, Cohen’s $d .36$).

Multiple linear regression analysis of all FMS™ components included in the regression model together as a predictor of TDI revealed a significant difference for FR ($r^2 .37$, Durbin Watson 2.21, $p = 0.01$, $F = 2.54$). Combined sample analysis produced the following values: ($r^2 .149$, Durbin Watson 2.37, $p = 0.12$, $F = 1.55$) and MR analysis demonstrated the following values: ($r^2 .18$, Durbin Watson 2.51, $p = 0.69$, $F = 0.75$). FMS™ components had a medium Cohen’s $d$ effect size for combined sample (.39) and MR (.42) and a large effect size for FR (.61).23 Multiple linear regression analysis of all FMS™ components with contusion injuries removed resulted in significant findings remaining for FR TDI ($r^2 .39$, Durbin Watson 2.23, $p = 0.03$, $F = 2.26$, Cohen’s $d .62$). Combined sample analysis was non-significant for TDI ($r^2 .14$, Durbin Watson 2.39, $p = 0.22$, $F = 1.33$, Cohen’s $d .38$). MR TDI demonstrated non-significant findings ($r^2 .24$, Durbin Watson 2.34, $p = 0.53$, $F = 0.93$, Cohen’s $d .49$).

Table 2 reports a stepwise multiple hierarchical linear regression of FMS™ components as a predictor of TDI and the hierarchical ordering of discrete FMS™ components, quantifying $r$ at each step. The ordering of individual elements therefore highlights the test elements with the greatest individual predictive power for FMS™ composite score. The Cohen’s $d$ effects size for FMS™ components were combined sample (.28), FR (.43) and MR (.34). Analysis with contusions removed did not alter significant findings for combined sample analysis and TDI ($p = 0.02$, $F = 3.97$), FR and TDI ($p = 0.01$, $F = 4.83$), MR and TDI ($p = 0.19$, $F = 1.83$).

### Injury analysis

Table 3 reports independent t-test analysis of the FMS™ composite scores of injured and non-injured subjects. All assumptions were confirmed. There was a significant difference between combined sample non-injured and injured ($p = 0.01$). Mean FMS™ composite scores were highest in MR non-injured (15.53 ± 1.89) and lowest in FR injured (13.76 ± 2.70). Following the removal of contusion injuries the analysis was repeated and all assumptions were confirmed. A significant difference remained between combined sample non-injured and injured ($p = 0.03$, 95% CI 0.111-1.95).

There was a statistically significant difference between male and female groups (injured and non-injured) for FMS™ composite score ($p = 0.02$). There was a significant difference in FMS™ composite score between MR non-injured and FR injured subjects ($p = 0.01$). Partial eta squared ($\eta^2$) was 0.07 which is considered a medium effect size.23 All other comparisons were non-significant. Analysis was repeated with contusion injuries removed and the significant difference in FMS™ composite score between male and female groups (injured and non-injured) ($p = 0.03$) and between MR non-injured and FR injured subjects ($p = 0.01$) remained. All other comparisons were non-significant.

There was no significant difference in FMS™ composite score between combined sample ‘multiple injuries’ subjects and non-injured subjects ($p = 0.31$) or...
between combined sample ‘multiple injuries’ subjects and single injury subjects ($p = 0.76$). Analysis was repeated with contusion injuries removed and the non-significant findings for FMS™ composite score between combined sample ‘multiple injuries’ subjects and non-injured subjects ($p = 0.41$) and between combined sample ‘multiple injuries’ subjects and single injury subjects ($p = 0.86$) remained.

### ROC curve analysis

ROC curve analysis of FMS™ composite score demonstrated an area under the curve for differentiating between injured and non-injured players of combined: (0.39, standard error 0.05, asymptomatic 0.04, 95% CI 0.29-0.49); FR: (0.41, standard error 0.07, asymptomatic 0.23, 95% CI 0.27-0.55); MR: (0.38, standard error 0.08, asymptomatic 0.11, 95% CI

---

### Table 2. Stepwise multiple hierarchical linear regression of FMS™ components as a predictor of total days injured.

<table>
<thead>
<tr>
<th>Group</th>
<th>$r^2$</th>
<th>Pearson r</th>
<th>DW</th>
<th>F- value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS RSM LIL</td>
<td>.06</td>
<td>RSM -.19</td>
<td></td>
<td>2.35</td>
<td>0.02*</td>
</tr>
<tr>
<td>RSM LIL LSLR LHS</td>
<td>.08</td>
<td>LIL - .16</td>
<td></td>
<td>3.94</td>
<td></td>
</tr>
<tr>
<td>RSM LIL LSLR LHS RHS LRS</td>
<td>.08</td>
<td>LSLR -.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LHS -.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RHS -.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LRS -.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR LIL LRS</td>
<td>.14</td>
<td>LIL -.34</td>
<td></td>
<td>2.29</td>
<td>0.01*</td>
</tr>
<tr>
<td>LIL LRS RIL RHS</td>
<td>.16</td>
<td>LRS -.25</td>
<td></td>
<td>4.81</td>
<td></td>
</tr>
<tr>
<td>LIL LRS RIL RHS RSM LHS</td>
<td>.19</td>
<td>RIL -.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RHS -.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RSM-.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LHS -.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR LHS RHS</td>
<td>.07</td>
<td>LHS -.26</td>
<td></td>
<td>2.47</td>
<td>0.17</td>
</tr>
<tr>
<td>LHS RHS PU RSM</td>
<td>.11</td>
<td>RHS -.19</td>
<td></td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>LHS RHS PU RSM LIL LSLR</td>
<td>.12</td>
<td>PU -.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RSM -.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LIL -.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LSLR -.07</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CS:** Combined Sample, **FR:** Female Rugby, **MR:** Male Rugby, **RSM:** Right Shoulder Mobility; **LIL:** Left In-line Lunge, **LSLR:** Left Straight Leg Raise; **LHS:** Left Hurdle Step; **RHS:** Right Hurdle Step; **LRS:** Left Rotary Stability; **RIL:** Right In-line Lunge, **PU:** Push Up; **DW:** Durbin Watson

* Significant at $p < 0.05$

---

### Table 3. FMS™ composite scores of injured and non-injured participants.

<table>
<thead>
<tr>
<th>Group</th>
<th>FMS™ (Mean/SD)</th>
<th>p value (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSNI</td>
<td>15.12 (2.31)</td>
<td>0.01* (0.21-1.81)</td>
</tr>
<tr>
<td>CSI</td>
<td>14.11 (2.42)</td>
<td></td>
</tr>
<tr>
<td>MRNI</td>
<td>15.53 (1.89)</td>
<td>0.06 (-0.45-2.11)</td>
</tr>
<tr>
<td>MRI</td>
<td>14.40 (2.44)</td>
<td></td>
</tr>
<tr>
<td>FRNI</td>
<td>14.53 (2.44)</td>
<td>0.22 (-0.46-1.99)</td>
</tr>
<tr>
<td>FRI</td>
<td>13.76 (2.70)</td>
<td></td>
</tr>
</tbody>
</table>

**CSNI:** Combined Sample Not Injured, **CSI:** Combined Sample Injured, **MRNI:** Rugby Male Rugby Not Injured, **MRI:** Male Rugby Injured, **FRNI:** Female Rugby Not Injured, **FRI:** Female Rugby Injured; **SD:** Standard Deviation, **MD:** Mean Difference

* Significant at $p < 0.05$
0.23-0.52). Figure 1 presents ROC curve combined samples analysis of FMS™ composite score, DS and PU. Figure 2 reports presents analysis of SM, SLR, and RS. Figure 3 presents ROC combined samples analysis of ILL and HS.

For FMS™ individual components the area under the curve of FR PU (0.58, standard error 0.08, asymptomatic 0.12, 95% CI 0.23-0.52); MR right RS (0.52, standard error 0.08, asymptomatic 0.85, 95% CI 0.36-0.67) were the best FMS™ components at differentiating between injured and non-injured subjects. Figure 4 reports ROC analysis of FR PU. Table 4 reports ROC curve sensitivity and specificity using

**Figure 1.** ROC curve pooled analysis of FMS composite score, deep squat, trunk stability push up.  
FMS: Functional Movement Screen; DS: Deep Squat; PU: Push Up

**Figure 2.** ROC curve pooled analysis of shoulder mobility, straight leg raise and rotary stability  
RSM: Right Shoulder Mobility; LSM: Left Shoulder Mobility; RSLR: Right Straight Leg Raise; LSLR: Left Straight Leg Raise; RRS: Right Rotatory Stability; LRS: Left Rotatory Stability

**Figure 3.** ROC curve pooled analysis in-line lunge and hurdle step  
RIL: Right In-line Lunge; LIL: Left In-line Lunge; RHS: Right Hurdle Step; LHS: Left Hurdle Step

**Figure 4.** ROC curve analysis of female rugby push up  
PU: Push Up
FMS™ composite score values from 11.5 to 14.5 as a predictor of injury cut off. The following cut of points were identified for FMS™ composite score: Combined sample 11.5; FR 11.5, MR 11.5. ROC analysis with contusions removed did not alter FMS™ composite findings to any great extent with the following values obtained: combined: (0.38, standard error 0.05, asymptomatic 0.04, 95% CI 0.27-0.49); FR: (0.38, standard error 0.08, asymptomatic 0.15 (95% CI 0.24-0.53); MR: (0.38, standard error 0.08, asymptomatic 0.13, 95% CI 0.22-0.53). FR PU and MR right RS remained the best FMS™ components at differentiating between injured and non-injured subjects with no change in values.

**Match and training exposure**
Combined sample match and training time was 230341 mins (1935.63 ± 982.19), combined sample match time was 67961 mins (571.1008 ± 367.96), combined sample training time was 162380 mins (1364.54 ± 714.50). FR combined sample match and training time was 101601 mins (1563.09 ± 822.30), match time was 29161 mins (448.63 ± 369.29) and training time was 72440 mins (1114.47 ± 557.21). MR combined sample match and training time was 128740 mins (2384.07 ± 977.87), match time was 38800 mins (718.52 ± 310.20) and training time was 89940 mins (1665.56 ± 769.84).

**Injury rate**
Table 5 reports injury rates and TDI in FR and MR. Seventy-two injuries (FR 34 (47%), MR 38 (53%)) occurred in 28 FR and 25 MR. For FR two players suffered two injuries and two players suffered three injuries. For MR 9 players suffered two injuries and two players suffered three injuries. For FR 7 (21%) injuries occurred in training and 27 (79%) in a match and for MR 8 (21%) injuries occurred in training and 30 (79%) in a match. One RM suffered a reinjury. All injuries were from a contact or non-contact mechanism.

**Injury severity**
For FR the following injury severity was recorded: 28 days+ (1, 1(100%) contact), 8-28 days (23, 16 (70%) contact), 4-7 days (6, 3 (50%) contact), 2-3 days (4, 2 (50%) contact). For MR the following injury severity was recorded 28 days+ (7, 7 (100%) contact), 8-28 days (9, 7 (53%) contact), 4-7 days (6, 3 (50%) contact), 2-3 days (4, 2 (50%) contact).
days (27, 16 (59%) contact), 4-7 days (3, 2 (67%) contact), 2-3 days (0), Up to one day (1, 1 (100%) contact).

Injury type
Injury type is reported in Table 6. The most common injury in FR was latissimus dorsi muscle strain (5, 15%) and in MR was ankle ligament sprain (6, 16%).

DISCUSSION
The primary aim of the study was to determine whether FMS™ composite scores and FMS™ components can predict injury in FR and MR. There was a statistically significant ability of the FMS™ composite score to serve as a predictor of TDI for combined sample and FR results however the $r^2$ values (Table 1) suggest that FMS™ composite score is a weak predictor of TDI. FMS™ composite score had a small Cohen's $d$ effect size for combined sample and MR and was approaching a medium effect size for FR in relation to TDI. These findings of the limited predictive value of FMS™ composite score may be due in part to the FMS™ test not being a unitary construct. Multiple linear regression analysis with all FMS™ individual components demonstrated that FMS™ individual components were a statistically significant predictor of 37.4% of the variation in TDI in FR which highlights contribution of these individual components in comparison to the FMS™ composite score. FMS™ components had a medium effect size for combined sample and MR and a large effect size for FR. Therefore, clinicians involved in injury prevention should consider that potential gender differences may exist when designing an injury prevention program.

Stepwise multiple hierarchical linear regression (Table 2) demonstrated significant findings for FR and demonstrates that LIL and LRS alone were able to predict 13.6% of variance in TDI and the addition of four more components increased this predictive

| Table 5. Injury rates, total days injured (TDI) and contact and non-contact injuries. |
|---------------------------------|--------|--------|--------|--------|
| Group             | TI & MI | TI/1000 hrs | MI/1000 hrs | Contact |
|                   | /1000 hrs |            |            | injuries | Non-contact |
|                   |         |            |            | (n)     | injuries (n) |
| CS                | 18.75   | 5.54       | 50.32      | 48      | 24 (6T,18M) |
|                   |         |            |            | (9T, 39M) |            |
| FR                | 20.08   | 5.80       | 55.56      | 22      | 12 (3T,9M) |
|                   |         |            |            | (4T, 18M) |            |
| MR                | 17.71   | 5.34       | 46.30      | 26      | 12 (3T, 9M) |
|                   |         |            |            | (5T, 21M) |            |
| TDI (Mean/SD)     |         |            |            |         | 1319 (11.06 ± 16.24) |
|                   |         |            |            |         | 516 (8.06 ± 12.50) |
|                   |         |            |            |         | 803 (14.60 ± 19.26) |

CS; Combined sample, FR; Female Rugby Players, MR; Male Rugby Players, TI; Training Injury, MI; Match Injury HRS; Hours, n; number, SD; Standard Deviation, T; Training, M; Match

<table>
<thead>
<tr>
<th>Table 6. Injury type.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury type</td>
</tr>
<tr>
<td>Ankle ligament sprain</td>
</tr>
<tr>
<td>Ankle contusion</td>
</tr>
<tr>
<td>Knee ligament sprain</td>
</tr>
<tr>
<td>Knee contusion</td>
</tr>
<tr>
<td>Rotator cuff strain</td>
</tr>
<tr>
<td>Shoulder contusion</td>
</tr>
<tr>
<td>Shoulder dislocation</td>
</tr>
<tr>
<td>Hip contusion</td>
</tr>
<tr>
<td>Adductor strain</td>
</tr>
<tr>
<td>Latissimus dorsi muscle strain</td>
</tr>
<tr>
<td>Hamstring strain</td>
</tr>
<tr>
<td>Quadriceps strain</td>
</tr>
<tr>
<td>Gastrocnemius strain</td>
</tr>
<tr>
<td>Wrist sprain</td>
</tr>
<tr>
<td>Finger contusion</td>
</tr>
<tr>
<td>Dislocated finger</td>
</tr>
<tr>
<td>Rib contusion</td>
</tr>
<tr>
<td>Concussion</td>
</tr>
</tbody>
</table>

Abbreviations: FR; Female Rugby Players, MR; Male Rugby Players
ability to 19.1%. Future FR screening could consider these two components if time constraints existed. RSM, LIL, LHS and RHS featured in the top six predictors of TDI across combined, FR and MR analysis and therefore future studies may wish to investigate the impact of these components. However caution must be observed as $r^2$ values indicated that none of the individual components were a strong predictor. The effect size for FMS components was small for combined sample and medium for FR and MR.

The secondary aim was to report injury demographics and to determine whether differences exist in the FMS scores of injured and non-injured subjects. FR training injury rates of 5.80 injuries/1000 hours and MR training injury rate of 5.34 injuries/1000 hours were similar to the 5.5 injuries/1000 hours in both males and females reported in American collegiate rugby union.14 The similarity between FR and MR total injury rates is in contrast to the reported the overall incidence rate which was 30% higher for men than women in intercollegiate club rugby players15 however comparison is limited by the different method utilized for calculating injury rate with this study15 utilizing an injury incidence rate per 10000 athlete exposures. FR and MR match injury rates of 55.56 injuries/1000 hours and 46.30/1000 hours were higher than those previously reported of 17.1 injuries/1000 hours in FR and 16.9 injuries/1000 hours in MR.14 However this study14 failed to record training duration exposure and made calculations based on practice hours exposure which limits comparison. The match injury rate in MR is similar to the match injury rate of 47 injuries/1000 hours.24 In amateur male rugby players (20-24 years) a match injury rate of 13.95/1000 hours has been reported25 while female match injury rates of 20.5/1000 hours have been reported in participants in elite senior women26 which are much lower than the current study. Such variations may be explained by varying injury recording methodologies and that higher skilled players may be more adept at avoiding contact injuries. In agreement with previous findings14 most injuries were contact injuries (67%) highlighting the physical demands of rugby. The similarity between injury rates in male and females in the current study may suggest that at university level, differences observed in the professional game in terms of the contact nature of the game are reduced.

Combined sample analysis of mean FMS composite score of injured and non-injured subjects (Table 3) revealed a significant difference ($p = 0.01$), however separate gender analysis revealed no significant difference for FR ($p = 0.22$) and MR ($p = 0.06$). The mean FMS composite scores of injured subjects was lower than non-injured subjects in both FR $13.76 (\pm 2.70) v 14.53 (\pm 2.44)$ and MR $14.40 (\pm 2.44) v 15.53 (\pm 1.89)$. Mean FR FMS injured scores were below the increased risk of injury cut off point of $\leq 14$ reported in female collegiate athletes.6 In male American football players a combination of at least one movement asymmetry and a score $< 14$ had an injury specificity of 0.87.27 In the current study the limited number of severe injuries ($n = 8$) prevented meaningful statistical analysis however previous findings in male rugby players who suffered a severe injury reported significantly lower FMS composite score and differences existed between contact injured and non-injured groups in DS, ILL and SLR.28 The current finding of only one reinjury is important as the presence of a large number of subjects with reinjuries may bias the sample due to the presence of ‘injury prone’ individuals, however this was not a problem within the study. The current study did not measure previous injury which has been identified as a risk factor for injury12,13 as self-reported injury is prone to bias. However the tertiary aim was to report differences between ‘multiple injuries’ subjects and non-injured and single injury subjects. Combined sample analysis of FMS composite score of ‘multiple injuries’ subjects revealed no significant difference between these subjects and non-injured subjects ($p = 0.31$) and single injury subjects ($p = 0.76$). This finding suggests that the FMS composite score may not be a factor in the development of multiple injuries however analysis is limited by the small sample of subjects who had multiple injuries ($n = 15$, contusions not removed) which also prevented separate gender analysis. Regression analysis regarding contributors to ‘multiple injuries’ subjects was not advocated due to the small sample size.

ROC curve analysis demonstrated that the FR, PU (.58), MR, and right RS (.52) were the best FMS components at differentiating between injured and non-injured subjects however these values cannot
be considered diagnostic as 0.5 can be considered a chance level. ROC curve analysis allowed calculation of a score that provided sensitivity and specificity for the identification of injured participants. Analysis indicated that for the combined sample group a score of 11.5 provided a sensitivity of .89 and specificity of .92 while for FR a score 11.5 provided a sensitivity of .90 and a specificity of .86 and for MR a score of 11.5 provided a sensitivity of .88 and a specificity of 1.00. These values may aid injury management and training load monitoring by allowing coaching staff to implement intervention programs to improve movement competency and/or adjust workload when a specific FMS™ value is achieved which might be suggestive of potential injury. In MR, the SLR test detected 96% of severe injuries and that the odds of a severe injury were 9.4 times greater in those with an SLR ≤ 2. However specificity was low (0.29) and many players who were below this cut off did not suffer severe injuries and a combined sample ILL and SLR were reported as most valuable for predicting injury.

The results of the current study indicate that FMS™ composite scores in non-injured rugby players are significantly greater than injured rugby players. A significant difference existed for FMS™ composite score between FR injured and MR non-injured players. The cut off for injury diagnosis with similar measures of sensitivity and specificity is 11.5 for FR and MR. These findings have value for the practitioner as they demonstrate the potential benefits of using quantifiable objective measures such as the FMS™ to monitor potential injury development. Players who are identified as being potentially at risk of injury may benefit from repeated FMS™ screening to monitor FMS™ scores. Intervention programs that aim to alter movement patterns can be implemented and the subsequent effect on FMS™ score monitored. It is of paramount importance that practitioners identify movement inefficiency that may produce abnormal movement patterns and injury. Minimal differences for match and training injury rates between FR and MR may highlight the increasing physical nature of FR. In this study seven out of eight severe injuries occurred in MR and therefore differences in injury severity require a further prospective cohort study with a larger sample size, and with more FR players.

The predictive capacity of FMS™ composite score to predict TDI was limited and the use of discrete components had greater predictive capacity particularly within FR were only two components (LIL, LRS) had a predictive capacity of 13.6%, however this should be considered a low predictive capability and may highlight that FMS injury cut off scores are more useful. With regard to potential injury development the importance of the DS and SLR has been highlighted in competitive distance runners and the ILL in athletes. Future studies may wish to consider performing the FMS™ post injury when participants return to play to allow comparison of any potential alterations in FMS™ scores.

With regard to the final aim of the study, statistical analysis was performed with contusion injuries removed based on the possibility that some contusion injuries may be due to chance and therefore the identification of whether these injuries are likely to occur might be difficult via the FMS™. The removal of contusion injuries made no change to the significant findings that were observed when all injuries were included. Tackling is associated with a high injury rate and rugby players should be taught proper tackling technique and high levels of agility are required to evade tackles. The ability to evade technique could potentially be enhanced by training using FMS™ movements. The ILL has been highlighted as the primary predictor of T-test agility performance in female and male rugby union players and it is possible that progressing from FMS™ movements into rugby specific movements such as cutting and offloading the ball may be beneficial and aid agility and tackle avoidance. The relationship between performance and injury requires further investigation. One focus could be whether specific functional movements of the FMS™ such as the ILL, DS, PU which form movements of some key rugby movements such as offloading, retrieving the ball from the ground and returning to standing following a tackle have greater importance when attempting to enhance performance and rehabilitate a player following injury. Future studies could consider whether the high prevalence of contact injuries are due to poor technique in tackling or due to other contact related movements.

Some limitations exist in the current study, as the correlation coefficients and statistical power of
regression analysis is influenced by the number of participant and variables. This study used three different types of regression analyses to improve the robustness of the methodology. The prospective nature of this study provided a comprehensive form of injury surveillance and prevented recall bias. Previous research has highlighted the multifactorial nature of injury10,11 and that injury etiology occurs in a dynamic recursive fashion11 as risk factors can change during sport exposure. The authors acknowledge that injury is multifactorial and therefore although the use of the FMS™ is advocated in the identification of injury in rugby it may potentially be used in the context of an injury prevention program that considers factors such as previous injury and how multiple injury risks may interact. The FMS™ is one potential tool that may identify movement patterns that potentially predispose an athlete to injury.

CONCLUSION
The findings of the current study indicate that the FMS™ can be used to identify those players with the potential to develop injury and the injury cut off point of 11.5 in FR and MR may aid identification of these individuals. Mean FMS™ composite scores are lower in both injured FR and MR in comparison to non-injured players and the individual components of the FMS™ are a more valuable predictor of injury than FMS™ composite score. Injury rates between FR and MR are similar with FR match injury rates higher than MR which maybe reflective of the increasing physical nature of female rugby. The FMS™ composite score of ‘multiple injuries’ players was not statistically different to non-injured and single injury players and this may provide a focus for future research.

REFERENCES


ABSTRACT

Background: A new functional movement assessment, known as the Fusionetics™ Movement Efficiency (ME) Test, has recently been introduced in the literature. Before the potential clinical utility of the ME Test can be examined, the reliability of this assessment must be established.

Purpose: To examine the intra-rater test-retest reliability of the Fusionetics™ ME Test.

Study Design: Cross-sectional.

Methods: ME Test data were collected among 23 (6 males, 17 females) university students (mean ± SD, age = 25.96 ± 3.16 yrs; height = 170.70 ± 9.96 cm; weight = 66.89 ± 12.67 kg) during sessions separated by 48 hours (Day 1, Day 2). All participants completed the seven sub-tests of the ME Test: 2-Leg Squat, 2-Leg Squat with Heel Lift, 1-Leg Squat, Push-Up, Shoulder Movements, Trunk Movements, and Cervical Movements. Overall ME Test scores and ME Test scores for each individual sub-test were calculated on a scale of 0 – 100 (worst – best) based on commonly observed movement compensations associated with each sub-test.

Results: Intraclass correlation coefficients (ICC_{3,1}) statistics indicated that the intra-rater test-retest reliability of the Overall ME Test and individual sub-tests ranged from fair-to-excellent (ICC_{3,1} range = 0.55 – 0.84). Statistically significant differences in ME Test scores were identified between Day 1 and Day 2 among the 2-Leg Squat with Heel Lift (p = 0.015) and Cervical Movements (p = 0.005) sub-tests. In addition, a large range in the standard error of the measure (SEM) and minimal detectable change values (MDC_{90%}, MDC_{95%}) were identified within individual sub-tests of the ME Test (SEM range = 7.05 – 13.44; MDC_{90%} range = 16.40 – 31.27; MDC_{95%} range = 19.53 – 37.25), suggesting that the response stability varies among these individual sub-tests. Prevalence-adjusted bias-adjusted kappa statistics (κ_{PABA}) suggest that 55 of the 60 (92%) individual movement compensations hold moderate-to-almost perfect intra-rater test-retest reliability (κ_{PABA} range = 0.30 – 1.00).

Conclusions: Excellent intra-rater test-retest reliability of the Overall ME Test score was identified, and thus, clinicians can reliably utilize the Fusionetics™ ME Test to assess change in functional movement quality across time. However, caution should be taken if utilizing an individual sub-test to assess functional movement quality over time.

Level of Evidence: 2b

Keywords: Functional movement quality assessment, movement screening, movement system, response stability, systematic bias

CORRESPONDING AUTHOR

David J. Cornell, PhD, CSCS, EP-C
Human Performance & Sport Physiology Laboratory
Pavilion – Physical Therapy & Athletic Training, Suite 350
3409 N. Downer Ave
Milwaukee, WI 53211-2956
E-mail: david_cornell@uml.edu
INTRODUCTION

Previous research has identified relationships between functional movement quality and musculoskeletal injury risk, as well as athletic performance and fitness.\(^1\) As a result, the utilization of various movement screening assessments by practitioners and clinicians to assess functional movement quality has grown tremendously over recent years.\(^2\) Such assessments include: the Functional Movement Screen (FMS™), the Landing Error Scoring System (LESS), several different single-leg squat screens, and various drop and/or tuck jump assessments.\(^3\)

Recently, a new assessment of functional movement quality has been introduced in the literature,\(^4\) known as the Fusionetics™ Movement Efficiency (ME) Test. This assessment was developed by Fusionetics, LLC (Milton, GA) and is associated with the Fusionetics™ Human Performance System. Similar to the FMS™,\(^6\) the ME Test utilizes seven sub-tests that require an individual to complete various movement patterns. However, the ME Test is graded based on the presence of specific movement compensations that are commonly observed during each sub-test. The Fusionetics™ Human Performance System then uses computer-based proprietary algorithms to generate a 0 – 100 (worst – best) score based on the movement compensations observed throughout the entire assessment, known as the Overall ME Test score, as well as an ME Test score for each individual sub-test.

Due to the utilization of discrete individual movement compensations in the scoring algorithms, the ME Test scores may be sensitive to changes in functional movement quality as a result of various corrective exercise interventions that address the specific movement compensations identified during the sub-tests. Due to previous research questioning the clinical utility of the FMS™ to monitor changes in movement quality,\(^5\) the ME Test may hold potential to be a more valid and/or clinically useful assessment of functional movement quality. However, before the validity or clinical utility of the ME Test can be examined, the reliability and response stability of the assessment must first be established.\(^10\)

Therefore, the purpose of the current study was to examine the intra-rater test-retest reliability and response stability of the Fusionetics™ ME Test.

METHODS

Participants

Twenty-three participants (6 males, 17 females) with no prior exposure to the ME Test or the Fusionetics™ Human Performance System volunteered to participate in this study (mean ± SD, age = 25.96 ± 3.16 yrs; height = 170.70 ± 9.96 cm; weight = 66.89 ± 12.67 kg; body mass index = 22.80 ± 2.80 kg/m\(^2\)). All participants were current students at the University of Wisconsin-Milwaukee (Milwaukee, WI). Participants were free of any musculoskeletal injury or muscular pain that required medical attention for the three months prior to participating in the study. All components of this study protocol were approved by the Institutional Review Board of the University of Wisconsin-Milwaukee and all participants provided written informed consent to this protocol prior to any data collection.

Protocol

All participants attended two data collection sessions (Day 1, Day 2) separated by 48 hours. To mitigate the potential influence of dehydration and/or muscle soreness, participants were instructed to not engage in any strenuous physical activity the 48 hours leading up to Day 1 of data collection, as well as in-between Day 1 and Day 2 data collection sessions. All ME Tests were administered, and subsequent data were collected, by the same researcher (K.T.E.) during both testing sessions. This researcher has been a certified athletic trainer (ATC) for 24 years, with greater than two years of prior experience administering the ME Test at the time of data collection. Participants were not informed of any test results between sessions.

ME Test

The ME Test was administered according to guidelines provided by Fusionetics, LLC (Appendix A). In brief, all participants completed the ME Test in athletic apparel and without shoes. Each participant completed each sub-test in the following order: 2-Leg Squat (Figure 1), 2-Leg Squat with Heel Lift (Figure 2), 1-Leg Squat (Figure 3), Push-Up (Figure 4), Shoulder Movements (Figure 5), Trunk Movements (Figure 6), and Cervical Movements (Figure 7). Participants were provided 5-10 trials of each sub-test and the most proficient trial (i.e., the least...
The number of compensations) of each sub-test was used for scoring purposes.

Each sub-test was scored in real-time in a binomial (yes/no) fashion based on a standard set of movement compensations commonly observed during each sub-test (Appendix B). In total, 60 compensations are scored across all sub-tests of the ME Test. After scoring each sub-test, these binomial data were then entered into the Fusionetics™ Human Performance System. This online platform utilizes a proprietary algorithm to calculate a ME Test score for the overall assessment (i.e., the Overall ME Test score), as well as a ME Test score for each individual sub-test. These ME Test scores are considered interval-level data and range from 0 – 100 (worst – best).
Statistical Analyses

In order to assess the intra-rater test-retest reliability of the interval ME Test score data, two-way mixed effects model (3,1) intraclass correlation coefficients (ICC\textsubscript{3,1}) were utilized.\textsuperscript{11} In addition, to examine for potential systematic bias,\textsuperscript{12} separate repeated measure analyses of variance (RM ANOVAs) were calculated between Day 1 and Day 2 ME Test scores. All ICC\textsubscript{3,1} statistics and RM ANOVAs were calculated using IBM SPSS 22 software (IBM Corp., Armonk, NY) and an alpha ≤ 0.05 determined statistically significant differences for all RM ANOVAs.

The response stability of the ME Test scores were further examined by calculating the standard error of the measure (SEM) statistics.\textsuperscript{13} SEM statistics were calculated by taking the square root of the mean square of the residual term ($\sqrt{MS_e}$) from the RM ANOVAs.\textsuperscript{11}

---

Figure 4. 1-Push-Up sub-test, A: Start Position; B: End Position.

Figure 5. Shoulder Movements sub-test, A: Shoulder Flexion – Start Position; B: Shoulder Flexion – End Position; C: Shoulder Internal Rotation – Start Position; D: Shoulder Internal Rotation – End Position; E: Shoulder External Rotation – Start Position; F: Shoulder External Rotation – End Position; G: Shoulder Horizontal Abduction – Start Position; H: Shoulder Horizontal Abduction – End Position.
Finally, minimal detectable change values at both 90% (MDC_{90%}) and 95% (MDC_{95%}) levels of confidence were calculated based upon the previously calculated SEMs (MDC_{90%} = SEM × 1.65 × √2; MDC_{95%} = SEM × 1.96 × √2, respectively) in order to provide practitioners with both a liberal and a conservative assessment of ME Test score change characteristics. ICC_{3,1} statistics were interpreted according to guidelines previously suggested in the literature: poor (ICC_{3,1} ≤ 0.39); fair (0.40 ≤ ICC_{3,1} ≤ 0.59); good (0.60 ≤ ICC_{3,1} ≤ 0.74); and excellent (ICC_{3,1} ≥ 0.75). In order to assess the intra-rater test-retest reliability of the binomial movement compensation data of each individual sub-test of the ME Test, percent observed agreement (%) and kappa statistics were calculated. However, to correct for asymmetrical distribution of the binomial data, prevalence-adjusted bias-adjusted kappa statistics (κ_{PABA}) were calculated, opposed to standard kappa statistics. κ_{PABA} statistics were calculated using Diagnostic and Agreement Statistics (DAG_Stat, Parkville, Victoria, Australia) open source statistical software. κ_{PABA} statistics were interpreted according to guidelines previously suggested in the literature: poor (κ_{PABA} < 0.00); slight (0.00 ≤ κ_{PABA} ≤ 0.20); fair (0.21 ≤ κ_{PABA} ≤ 0.40); moderate (0.41 ≤ κ_{PABA} ≤ 0.60); substantial (0.61 ≤ κ_{PABA} ≤ 0.80); and almost perfect (κ_{PABA} ≥ 0.81).

RESULTS

Descriptive statistics (mean ± SD) of Day 1 and Day 2 ME Test scores, as well as ICC_{3,1}, SEM, MDC_{90%}, MDC_{95%} statistics are provided in Table 1. The ICC_{3,1} statistic of 0.84 indicates excellent intra-rater test-retest reliability of the Overall ME Test scores. In addition, the ICC_{3,1} statistics indicate that the intra-rater test-retest reliability of the individual sub-tests...
ranged from fair-to-excellent ($\text{ICC}_{3,1}$ range = 0.55 – 0.84). However, results of the RM ANOVAs identified statistically significant differences in ME Test scores between Day 1 and Day 2 among the 2-Leg Squat with Heel Lift ($p = 0.015$) and Cervical Movements ($p = 0.005$) sub-tests, indicating potential systematic bias within these two sub-tests. No significant differences were identified between Day 1 and Day 2 among the Overall ME Test scores, as well as among the ME Test scores of the other individual sub-tests. The MDC$_{95\%}$ statistic of 12.68 associated with the Overall ME Test score indicates that a change in ME Test score of 12.68 points is required for this change in overall functional movement quality to be considered “real” (i.e., outside of the error associated with the measure itself). However, a large range in SEM and MDC statistics were identified within the individual sub-tests of the ME Test (SEM range = 7.05 – 13.44; MDC$_{90\%}$ range = 16.40 – 31.27; MDC$_{95\%}$ range = 19.53 – 37.25), suggesting that the response stability varies among the individual sub-tests.

The intra-rater test-retest reliability statistics of the binomial movement compensation data, and the associated interpretation of these statistics, are provided in Tables 2 – 8. In brief, the $\kappa_{\text{PABA}}$ statistics suggest that the test-retest reliability of the individual movement compensations ranged from fair-to-almost perfect ($\kappa_{\text{PABA}}$ range = 0.30 – 1.00), with an average observed agreement of 85.7% (range = 65% – 100%). Based on the guidelines of $\kappa_{\text{PABA}}$ statistic interpretations previously suggested in the literature, 22 out of 60 (37%) of the possible movement compensations have almost perfect reliability; 19 out of 60 (32%) of the possible movement compensations have substantial reliability; 14 out of 60 (23%) of the possible movement compensations have moderate reliability; 5 out of 60 (8%) of the possible movement compensations have fair reliability; and 0 out of 60 (0%) of the possible movement compensations have slight or poor reliability. Furthermore, these results suggest that 55 of the 60 (92%) individual movement compensations hold moderate-to-almost perfect intra-rater test-retest reliability, with 41 of the 60 (68%) individual movement compensations holding substantial-to-almost perfect intra-rater test-retest reliability.

**DISCUSSION**

The purpose of the current study was to examine the intra-rater test-retest reliability and response stability of a relatively new functional movement assessment, known as the Fusionetics™ ME Test. Results of this study suggest that the Overall ME Test score holds excellent intra-rater test-retest reliability and that the individual sub-tests hold fair-to-excellent intra-rater test-retest reliability (Table 1). These results imply that the ME Test holds adequate intra-rater test-retest reliability for use among practitioners and clinicians. In addition, the ICC associated with the Overall ME Test in the current study ($\text{ICC}_{3,1} = 0.84$) is similar to the intra-rater test-retest ICCs associated with the FMS™ composite scores.

---

**Table 1.** ME Test intra-rater test-retest statistics.

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Descriptive Statistics (mean ± SD)*</th>
<th>Reliability and Response Stability Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
</tr>
<tr>
<td>Overall ME Test Score</td>
<td>50.27 ± 12.20</td>
<td>47.63 ± 10.42</td>
</tr>
<tr>
<td>ME Sub-Test Scores</td>
<td>Be</td>
<td>Be</td>
</tr>
<tr>
<td>2-Leg Squat</td>
<td>61.35 ± 16.94</td>
<td>61.79 ± 12.75</td>
</tr>
<tr>
<td>2-Leg Squat with Heel Lift†</td>
<td>74.64 ± 10.85</td>
<td>69.13 ± 11.41</td>
</tr>
<tr>
<td>1-Leg Squat</td>
<td>31.82 ± 12.92</td>
<td>31.53 ± 13.98</td>
</tr>
<tr>
<td>Push-Up</td>
<td>40.00 ± 24.12</td>
<td>43.48 ± 18.74</td>
</tr>
<tr>
<td>Shoulder Movements</td>
<td>44.02 ± 26.35</td>
<td>46.22 ± 23.82</td>
</tr>
<tr>
<td>Trunk Movements</td>
<td>22.83 ± 22.50</td>
<td>23.91 ± 27.67</td>
</tr>
<tr>
<td>Cervical Movements†</td>
<td>59.78 ± 35.94</td>
<td>47.83 ± 29.11</td>
</tr>
</tbody>
</table>

*All are scored 0 – 100 (worst – best)
†Different at $p < 0.05$; results of repeated measures analyses of variance (RM ANOVAs).
in the FMS™ literature. Specifically, Bonazza et al. recently calculated a pooled ICC statistic of 0.81 across the FMS™ literature.

Results of the current study also suggest that a change in Overall ME Test score of 12.68 points is required for this change in overall functional movement quality to be considered “real” (MDC = 12.68). This MDC value is associated with the error of the measure itself and is based upon the SEM calculated between the Day 1 and Day 2 ME Test scores (SEM = 4.57). Thus, a 12.68 increase in Overall ME Test score may represent a practically significant change in functional movement quality when the ME Test is being utilized among practitioners and clinicians to assess changes in the functional movement quality of an individual as a result of an intervention. Unlike the FMS™, the ME Test utilizes a 0 – 100 scoring scale for both the Overall ME Test score and each the sub-test score of the ME Test. As a result, even though

### Table 2. Intra-rater test-retest agreement of movement compensations observed during 2-Leg Squat sub-test of the ME Test.

<table>
<thead>
<tr>
<th>Compensation</th>
<th>Observed Agreement</th>
<th>(k_{	ext{PABA}})</th>
<th>(k_{	ext{PABA}}) Interpretation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Foot Out</td>
<td>70%</td>
<td>0.39</td>
<td>Fair</td>
</tr>
<tr>
<td>Left Foot Out</td>
<td>70%</td>
<td>0.39</td>
<td>Fair</td>
</tr>
<tr>
<td>Right Foot Flattens</td>
<td>85%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
<tr>
<td>Left Foot Flattens</td>
<td>87%</td>
<td>0.74</td>
<td>Substantial</td>
</tr>
<tr>
<td>Right Knee Moves In</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Left Knee Moves In</td>
<td>91%</td>
<td>0.83</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Right Knee Moves Out</td>
<td>78%</td>
<td>0.57</td>
<td>Moderate</td>
</tr>
<tr>
<td>Left Knee Moves Out</td>
<td>85%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
<tr>
<td>Excessive Forward Lean</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Low Back Arches</td>
<td>65%</td>
<td>0.30</td>
<td>Fair</td>
</tr>
<tr>
<td>Low Back Rounds</td>
<td>100%</td>
<td>1.00</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Arms Fall Forwards</td>
<td>87%</td>
<td>0.74</td>
<td>Substantial</td>
</tr>
<tr>
<td>Right Heel of Foot Lifts</td>
<td>100%</td>
<td>1.00</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Left Heel of Foot Lifts</td>
<td>100%</td>
<td>1.00</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Right Asymmetrical Weight Shift</td>
<td>87%</td>
<td>0.74</td>
<td>Substantial</td>
</tr>
<tr>
<td>Left Asymmetrical Weight Shift</td>
<td>83%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
</tbody>
</table>

ME Test = Movement Efficiency Test; \(k_{	ext{PABA}}\) = prevalence-adjusted bias-adjusted kappa statistic.

*\(k_{	ext{PABA}}\) interpretation based on guidelines provided by Landis and Koch.

### Table 3. Intra-rater test-retest agreement of movement compensations observed during 2-Leg Squat with Heel Lift sub-test of the ME Test.

<table>
<thead>
<tr>
<th>Compensation</th>
<th>Observed Agreement</th>
<th>(k_{	ext{PABA}})</th>
<th>(k_{	ext{PABA}}) Interpretation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Foot Out</td>
<td>87%</td>
<td>0.74</td>
<td>Substantial</td>
</tr>
<tr>
<td>Left Foot Out</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Right Foot Flattens</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Left Foot Flattens</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Right Knee Moves In</td>
<td>100%</td>
<td>1.00</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Left Knee Moves In</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Right Knee Moves Out</td>
<td>91%</td>
<td>0.83</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Left Knee Moves Out</td>
<td>83%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
<tr>
<td>Excessive Forward Lean</td>
<td>78%</td>
<td>0.57</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low Back Arches</td>
<td>74%</td>
<td>0.48</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low Back Rounds</td>
<td>100%</td>
<td>1.00</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Arms Fall Forwards</td>
<td>91%</td>
<td>0.83</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Right Asymmetrical Weight Shift</td>
<td>74%</td>
<td>0.48</td>
<td>Moderate</td>
</tr>
<tr>
<td>Left Asymmetrical Weight Shift</td>
<td>83%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
</tbody>
</table>

ME Test = Movement Efficiency Test; \(k_{	ext{PABA}}\) = prevalence-adjusted bias-adjusted kappa statistic.

*\(k_{	ext{PABA}}\) interpretation based on guidelines provided by Landis and Koch.
previous research by Teyhen et al. has examined the MDC of the FMS™, it is not possible to compare the MDC\textsubscript{95\%} of the ME Test identified in the current study to the MDC\textsubscript{95\%} of the FMS (12.68 vs. 2.07, respectively).

However, since several recent studies have failed to identify improvements in FMS™ scores as a result of targeted corrective or functional training programming, the clinical utility of the FMS™ for use

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
\textbf{Compensation} & \textbf{Observed Agreement} & \textbf{K\textsubscript{PABA}} & \textbf{K\textsubscript{PABA} Interpretation*} \\
\hline
Right Leg – Foot Flattens & 78\% & 0.57 & Moderate \\
Left Leg – Foot Flattens & 78\% & 0.57 & Moderate \\
Right Leg – Knee Moves In & 87\% & 0.74 & Substantial \\
Left Leg – Knee Moves In & 100\% & 1.00 & Almost Perfect \\
Right Leg – Knee Moves Out & 100\% & 1.00 & Almost Perfect \\
Left Leg – Knee Moves Out & 100\% & 1.00 & Almost Perfect \\
Right Leg – Uncontrolled Trunk & 91\% & 0.83 & Almost Perfect \\
Left Leg – Uncontrolled Trunk & 83\% & 0.65 & Substantial \\
Right Leg – Loss of Balance & 83\% & 0.65 & Substantial \\
Left Leg – Loss of Balance & 96\% & 0.91 & Almost Perfect \\
\hline
\end{tabular}
\caption{Intra-rater test-retest agreement of movement compensations observed during 1-Leg Squat sub-test of the ME Test.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
\textbf{Compensation} & \textbf{Observed Agreement} & \textbf{K\textsubscript{PABA}} & \textbf{K\textsubscript{PABA} Interpretation*} \\
\hline
Head Moves Forward & 91\% & 0.83 & Almost Perfect \\
Scapular Dyskinesis & 83\% & 0.65 & Substantial \\
Low Back Arches / Stomach Protrudes & 87\% & 0.74 & Substantial \\
Knees Bend & 70\% & 0.39 & Fair \\
\hline
\end{tabular}
\caption{Intra-rater test-retest agreement of movement compensations observed during Push-Up sub-test of the ME Test.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
\textbf{Compensation} & \textbf{Observed Agreement} & \textbf{K\textsubscript{PABA}} & \textbf{K\textsubscript{PABA} Interpretation*} \\
\hline
Right Shoulder – Flexion: Compensation during movement / Unable to bring hand to wall & 74\% & 0.48 & Moderate \\
Left Shoulder – Flexion: Compensation during movement / Unable to bring hand to wall & 78\% & 0.57 & Moderate \\
Right Shoulder – Internal Rotation: Compensation during movement / Unable to bring hand to mid-line of trunk & 78\% & 0.57 & Moderate \\
Left Shoulder – Internal Rotation: Compensation during movement / Unable to bring hand to mid-line of trunk & 78\% & 0.57 & Moderate \\
Right Shoulder – External Rotation: Compensation during movement / Unable to bring hand to wall & 83\% & 0.65 & Substantial \\
Left Shoulder – External Rotation: Compensation during movement / Unable to bring hand to wall & 78\% & 0.57 & Moderate \\
Right Shoulder – Horizontal Abduction: Compensation during movement / Unable to bring hand to wall & 78\% & 0.57 & Moderate \\
Left Shoulder – Horizontal Abduction: Compensation during movement / Unable to bring hand to wall & 78\% & 0.57 & Moderate \\
\hline
\end{tabular}
\caption{Intra-rater test-retest agreement of movement compensations observed during Shoulder Movements sub-test of the ME Test.}
\end{table}
among practitioners and clinicians has been questioned. It has been previously suggested that a lack of responsiveness of the FMS™ scoring system may be a result of the 0 – 3 ordinal scoring scale of the FMS™ sub-tests may contribute to the equivocal clinical utility noted in the literature. Although a 0 – 100 scale has been introduced by developers of the FMS™, there is currently a lack of research utilizing this scoring scale. It is possible that the 0 – 100 scoring scale of the ME Test may prove to be more sensitive to changes in functional movement quality as a result of a targeted corrective exercise intervention, but further research to confirm this hypothesis is warranted.

In addition, the minimal clinically important difference (MCID), or the smallest change in which a patient/individual would consider to be beneficial, of the Overall ME Test score remains unidentified. Therefore, future research should explore the relationships between changes in ME Test scores as the result of an intervention with these individual's perceived benefits in functional movement quality. Such research would assist with determining the MCID associated with the ME Test and will help further elucidate the level of change in ME Test scores that are required to be clinically meaningful.

That said, systematic bias was potentially identified within the 2-Leg Squat with Heel Lift and Cervical Movements sub-tests, as significant differences ME Test scores were identified between Day 1 and Day 2, suggesting that systematic bias may be apparent within these specific sub-tests. It is possible that the differences between Day 1 and Day 2 are related to the number of movement compensations being assessed, differences in precise implementation of testing instructions for these sub-tests, and/or an expected amount of variability in movement quality across days. However, these potential mechanisms

---

**Table 7. Intra-rater test-retest agreement of movement compensations observed during Trunk Movements sub-test of the ME Test.**

<table>
<thead>
<tr>
<th>Compensation</th>
<th>Observed Agreement</th>
<th>$k_{pab}$</th>
<th>$k_{pab}$ Interpretation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Trunk Lateral Flexion:</td>
<td>83%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
<tr>
<td>Compensation during movement / Unable to touch lateral joint line of knee</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Trunk Lateral Flexion:</td>
<td>87%</td>
<td>0.74</td>
<td>Substantial</td>
</tr>
<tr>
<td>Compensation during movement / Unable to touch lateral joint line of knee</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Trunk Rotation:</td>
<td>96%</td>
<td>0.91</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Compensation during movement / Unable to rotate shoulder to midline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Trunk Rotation:</td>
<td>91%</td>
<td>0.82</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Compensation during movement / Unable to rotate shoulder to midline</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ME Test = Movement Efficiency Test; $k_{pab}$ = prevalence-adjusted bias-adjusted kappa statistic. *$k_{pab}$ interpretation based on guidelines provided by Landis and Koch.

**Table 8. Intra-rater test-retest agreement of movement compensations observed during Cervical Movements sub-test of the ME Test.**

<table>
<thead>
<tr>
<th>Compensation</th>
<th>Observed Agreement</th>
<th>$k_{pab}$</th>
<th>$k_{pab}$ Interpretation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Cervical Lateral Flexion:</td>
<td>74%</td>
<td>0.48</td>
<td>Moderate</td>
</tr>
<tr>
<td>Compensation during movement / Unable to side-bend half the distance to the shoulder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Cervical Lateral Flexion:</td>
<td>83%</td>
<td>0.65</td>
<td>Substantial</td>
</tr>
<tr>
<td>Compensation during movement / Unable to side-bend half the distance to the shoulder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Cervical Rotation:</td>
<td>87%</td>
<td>0.74</td>
<td>Substantial</td>
</tr>
<tr>
<td>Compensation during movement / Unable to rotate chin to shoulder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Cervical Rotation:</td>
<td>70%</td>
<td>0.39</td>
<td>Fair</td>
</tr>
<tr>
<td>Compensation during movement / Unable to rotate chin to shoulder</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ME Test = Movement Efficiency Test; $k_{pab}$ = prevalence-adjusted bias-adjusted kappa statistic. *$k_{pab}$ interpretation based on guidelines provided by Landis and Koch.
could only be considered speculative at this point and future research examining the potential variability in sub-tests scores across longer durations of time is required to further elucidate the potential, if any, influence of these factors. Furthermore, large ranges in the SEM and MDC statistics were identified within the individual sub-tests of the ME Test (Table 1). Taken together, these results indicate that the response stability varies among the individual sub-tests. Therefore, although the intra-rater test-retest reliability of the individual sub-tests ranged from fair-to-excellent, caution should be taken if utilizing a single sub-test of the ME Test to assess changes in functional movement quality and utilizing the Overall ME Test score may be more appropriate.

Similar to the results in the current study, previous research has also identified large, and sometimes conflicting, ranges in intra-rater test-retest reliability among the various FMS™ sub-tests in the FMS™ literature as well. Since it is possible that these ranges in FMS™ sub-test reliability may be contributing to the questionable construct of the FMS™ composite score, future research should also examine the factorial validity of the Overall ME Test score. Moreover, although both the ME Test and the FMS™ quantify functional movement quality, the variance shared between these two assessments remains unexplored. Therefore, future research should also examine the criterion-reference validity of the ME Test in relation to the already established FMS™ assessment.

Finally, since the Fusionetics™ Human Performance System utilizes movement compensations identified during each sub-test to calculate each ME Test score, it is also important to examine the consistency associated with identifying these specific movement compensations. As such, the intra-rater test-retest reliability of the binominal movement compensation data of each individual sub-test of the ME Test was examined as well. The results of the current study suggest that the intra-rater test-retest reliability of the individual movement compensations ranged from fair-to-almost perfect. Although a large range in κPABA statistics were observed (κPABA range = 0.30 – 1.00), it should be noted that the vast majority (92%) of the individual movement compensations held moderate-to-almost perfect intra-rater test-retest reliability and an average observed agreement of 85.7% was found between the movement compensations identified on Day 1 and Day 2. These results suggest that the individual movement compensations associated with the scoring of each sub-test of the ME Test hold adequate intra-rater test-retest reliability as well. Collectively, these results provide further support for the response stability in the scoring of the Overall ME Test score, as consistency in the identification of these movement compensations would theoretically be required to create consistency in this scoring process.

Beyond the support regarding the reliability of the ME Test scoring methods, the current study introduces to the literature preliminary insight into the level of change in ME Test scores that is required to hold practical relevance. To date, this information is unknown and these results provide clinicians and practitioners with initial scientific evidence to guide the use of the ME Test as a functional outcome measure within their practice. Specifically, there is a growing trend among clinicians and practitioners to prescribe specific corrective exercises in an attempt to improve many of the same movement compensations observed during the ME Test. For example, the targeted strengthening of the gluteus medius and other proximal musculature in an effort to mitigate dynamic knee valgus observed during movement. Based on this growing trend and the results of the current study, improvements in ME Test scores may indicate successful mitigation of the observed movement compensations as a result of the targeted corrective exercise programming. Such outcomes would provide additional rationale for the sensitivity of the ME Test and support for its use as a useful assessment tool. However, further research examining both the responsiveness of the ME Test and the efficacy of such corrective exercise programming is required.

Limitations

There are limitations to consider with the current study. Similar to other commercially available products that rely on a proprietary algorithm to generate an outcome, the proprietary nature of the ME Test scoring does not allow for practitioners and researchers to identify how various movement compensations are weighted within the scoring calculations. Due to this, the reproducibility of this study is not
generalizable without utilizing the Fusionetics™ Human Performance System. The current study did, however, examine the intra-rater test-retest reliability of the 60 total movement compensations for each individual sub-test as well. Since the vast majority (92%) of the individual movement compensations held moderate-to-almost perfect intra-rater test-retest reliability, it is likely that the response stability of the scoring criteria resulted in the fair-to-excellent intra-rater test-retest reliability identified within the ME Test scores.

The results of the current study can also only be generalized to college-aged university students, as reliability must be established within each sample population of interest. Therefore, future research examining the intra-rater test-retest reliability and MDC characteristics should be conducted among other various clinical populations of interest (e.g., collegiate & professional athletes, tactical athletes, etc.). In addition, the current study utilized live assessment methods during each testing session, which meets the intended utility of the movement screen. It is possible that the assessment of movement compensations, and thus, the scoring of each sub-test, will differ between live and post hoc video analysis methods. Although use of video to make the assessments could become a practical limitation a movement screen for a clinician, future research should examine if differences in assessment methods exist within the scoring of the ME Test.

Finally, the researcher who performed all ME Test assessments in the current study (K.T.E.), was an ATC with greater than two years of previous experience with conducting the ME Test on numerous individuals. As a result, future research should be conducted to examine the intra-rater test-retest reliability of practitioners and clinicians of other professional backgrounds (e.g., strength and conditioning [S&C] professionals, physical therapists [PTs], etc.), as well as the effect of training and familiarity with the ME Test on the intra-rater test-retest reliability among various practitioners and clinicians. Similarly, although preliminary data has been presented regarding the inter-rater reliability of the ME Test, further research investigating the consistency in ME Test scoring between raters, and the potential scoring biases between raters of differing professional backgrounds (e.g., S&C professionals vs. PTs vs. ATCs, etc.), should be explored as well.

CONCLUSIONS
In conclusion, results of the current study indicate that the Fusionetics™ ME Test holds adequate intra-rater test-retest reliability for use among practitioners and clinicians. Results of the current study also suggest that a 12.68 point change in Overall ME Test score may represent a practically significant change in functional movement quality when utilizing the ME Test to assess changes in the functional movement quality of an individual as a result of an intervention. However, caution should be taken by practitioners and clinicians if deciding to utilize an individual sub-test of the ME Test to quantify and/or monitor changes in functional movement quality.

REFERENCES


## Appendix A. Movement Efficiency (ME) Test Instructions Checklist.

<table>
<thead>
<tr>
<th>Sub-Tests</th>
<th>Participant Positioning</th>
<th>Tester Instructions / Participant Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Leg Squat</td>
<td>- Feet shoulder-width apart</td>
<td>- Perform 5 squats as if sitting into chair</td>
</tr>
<tr>
<td></td>
<td>- Toes pointing straight ahead</td>
<td>- Observe: front, side, &amp; back views</td>
</tr>
<tr>
<td></td>
<td>- Arms extended overhead</td>
<td></td>
</tr>
<tr>
<td>2-Leg Squat with Heel Lift</td>
<td>- Elevate heels approximately 2”</td>
<td>- Perform 5 squats as if sitting into chair</td>
</tr>
<tr>
<td></td>
<td>- Feet shoulder-width apart</td>
<td>- Observe: front, side, &amp; back views</td>
</tr>
<tr>
<td></td>
<td>- Toes pointing straight ahead</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Arms extending overhead</td>
<td></td>
</tr>
<tr>
<td>1-Leg Squat (completed bilaterally)</td>
<td>- Balancing on 1-leg, with hands on hips</td>
<td>- Perform 5 squats as if sitting into chair</td>
</tr>
<tr>
<td></td>
<td>- Toes pointing straight ahead</td>
<td>- Observe: front, side, &amp; back views</td>
</tr>
<tr>
<td></td>
<td>- Non-involved foot &amp; leg are neutral</td>
<td></td>
</tr>
<tr>
<td>Push-Up</td>
<td>- Assume a push-up position</td>
<td>- Perform 5-10 push-ups</td>
</tr>
<tr>
<td></td>
<td>- Hands outside shoulders, even with chest</td>
<td>- Observe: Side view</td>
</tr>
<tr>
<td></td>
<td>- Head looking at ground, cervical spine at neutral</td>
<td></td>
</tr>
<tr>
<td>Shoulder Movements (4 total movements completed bilaterally)</td>
<td>- Standing with back to wall</td>
<td>1. Flexion: Raise arm straight overhead, touch thumb to wall</td>
</tr>
<tr>
<td></td>
<td>- Feet hip-width apart, arms by sides</td>
<td>2. Internal Rotation: Elbows at 90°, rotate shoulder taking wrists forward toward mid-line of body</td>
</tr>
<tr>
<td></td>
<td>- Heels, buttocks, shoulders &amp; back of head touching wall</td>
<td>3. External Rotation: Elbows at 90°, rotate shoulder taking back of wrist to wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Horizontal Abduction: Hands together in front of body, reach back of wrist to wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*All of the above: Observe front &amp; side views; perform one arm at a time</td>
</tr>
<tr>
<td>Trunk Movements (2 total movements completed bilaterally)</td>
<td>- Standing with back to wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Feet shoulder-width apart, arms by sides</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Heels, buttocks, shoulders, &amp; back of head touching wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Rotation: Individual steps away from wall, places hands across shoulders</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Lateral Flexion: Side bend and slide hand down outside of leg to lateral knee joint line</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Rotation: Rotate upper body (maintaining a neutral pelvis/hips) each direction as far as possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*All of the above: Observe front &amp; side views; perform movement in each direction</td>
</tr>
<tr>
<td>Cervical Movements (2 total movements completed bilaterally)</td>
<td>- Feet shoulder-width apart, arms by sides</td>
<td>1. Lateral Flexion: Tip head, taking ear to shoulder</td>
</tr>
<tr>
<td></td>
<td>- Head in neutral position</td>
<td>2. Rotation: Rotate head and look over shoulder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*All of the above: Observe front &amp; side views; perform movement in each direction</td>
</tr>
</tbody>
</table>
## Appendix B. Movement Efficiency (ME) Test Grading Form.

### 2-LEG SQUAT

<table>
<thead>
<tr>
<th>Checkpoint</th>
<th>Compensation</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>View: Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot/Ankle</td>
<td>Foot Turns Out</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foot Flattens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>Knee Moves In (Valgus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knee Moves Out (Varus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>View: Side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-P-H-C</td>
<td>Excessive Forward Lean</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Back Arches</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Back Rounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>Arms Fall Forward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>View: Back</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot/Ankle</td>
<td>Heel of Foot Lifts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-P-H-C</td>
<td>Asymmetrical Weight Shift</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2-LEG SQUAT WITH HEEL LIFT

<table>
<thead>
<tr>
<th>Checkpoint</th>
<th>Compensation</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>View: Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot/Ankle</td>
<td>Foot Turns Out</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foot Flattens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>Knee Moves In (Valgus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knee Moves Out (Varus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>View: Side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-P-H-C</td>
<td>Excessive Forward Lean</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Back Arches</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Back Rounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>Arms Fall Forward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>View: Back</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-P-H-C</td>
<td>Asymmetrical Weight Shift</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 1-LEG SQUAT

<table>
<thead>
<tr>
<th>Checkpoint</th>
<th>Compensation</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>View: Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot/Ankle</td>
<td>Foot Flattens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>Knee Moves In (Valgus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knee Moves Out (Varus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-P-H-C</td>
<td>Uncontrolled Trunk: Flexion, Rotation, and/or Hip Shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss of Balance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

L-P-H-C = Lumbo-Pelvic-Hip-Complex.

Note: if not specifically indicated, a compensation is defined as any accessory motion utilized by the individual that is not required to complete the desired movement.
Appendix B. *Movement Efficiency (ME) Test Grading Form (continued)*

<table>
<thead>
<tr>
<th>PUSH-UP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Checkpoint</strong></td>
</tr>
<tr>
<td><strong>View: Side</strong></td>
</tr>
<tr>
<td>Spine</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>L-P-H-C</td>
</tr>
<tr>
<td>Knees</td>
</tr>
</tbody>
</table>

**SHOULDER MOVEMENTS**

<table>
<thead>
<tr>
<th>Checkpoint</th>
<th><strong>Compensation</strong></th>
<th><strong>Right</strong></th>
<th><strong>Left</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>View: Side</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>Flexion: Compensation during movement / Unable to bring hand to wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Internal Rotation: Compensation during movement / Unable to bring hand to mid-line of trunk</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>External Rotation: Compensation during movement / Unable to bring hand to wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal Abduction: Compensation during movement / Unable to bring hand to wall</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TRUNK MOVEMENTS**

<table>
<thead>
<tr>
<th>Checkpoint</th>
<th><strong>Compensation</strong></th>
<th><strong>Right</strong></th>
<th><strong>Left</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>View: Front</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spine</td>
<td>Trunk Lateral Flexion: Compensation during movement / Unable to touch lateral joint line of knee with fingers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trunk Rotation: Compensation during movement / Unable to rotate lateral aspect of shoulder to mid-line of sternum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CERVICAL MOVEMENTS**

<table>
<thead>
<tr>
<th>Checkpoint</th>
<th><strong>Compensation</strong></th>
<th><strong>Right</strong></th>
<th><strong>Left</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>View: Front</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spine</td>
<td>Cervical Lateral Flexion: Compensation during movement / Unable to side-bend neck so that ear is approximately half the distance to shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cervical Rotation: Compensation during movement / Unable to rotate chin to acromion of shoulder</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

L-P-H-C = Lumbo-Pelvic-Hip-Complex.
Note: if not specifically indicated, a compensation is defined as any accessory motion utilized by the individual that is not required to complete the desired movement.
ABSTRACT

**Background:** Wearable devices validly assess spatiotemporal running parameters (cadence, vertical oscillation and ground contact time), but the relationship between these parameters and lower limb loading parameters (loading rate, peak vertical ground reaction force [vGRF] and braking impulse) is unknown.

**Purpose:** To characterize changes in lower limb loading parameters in runners instructed to run with increased cadence or low vertical oscillation, and to determine whether the change in spatiotemporal parameters predicted the changes in lower limb loading parameters.

**Study Design:** Cross Sectional Cohort Study

**Methods:** Twenty healthy runners completed three running trials in three conditions: baseline, high cadence, and low vertical oscillation. Spatiotemporal parameters were measured with a wearable device and lower limb loading was measured using an instrumented treadmill. Spatiotemporal and loading parameters were analyzed between running conditions via a repeated measure ANOVA. A hierarchical regression model was used to determine if changes in spatiotemporal parameters predicted the change of loading parameters during conditions.

**Results:** High cadence and low oscillation conditions reduced average vertical loading rate (p = 0.013 and p = 0.002, respectively), instantaneous vertical loading rate (p = 0.022 and p = 0.001, respectively), and peak vGRF (p = 0.025 and p < 0.001, respectively). Braking impulse was significantly lower in the high cadence condition compared to baseline (p < 0.001), but not during the low oscillation (p = 1.000). The increase in cadence during the high cadence condition predicted the reduction of instantaneous vertical loading rate (r² = 0.213, p = 0.041) and braking impulse (r² = 0.279, p = 0.017). The reduction in vertical oscillation was more predictive of the change of peak vGRF in both running conditions (high cadence, r² = 0.436, p = 0.009; low oscillation r² = 0.748, p < 0.001).

**Conclusion:** While both higher cadence and lower vertical oscillation resulted in reduced loading rates during running, cueing to reduce vertical oscillation was more successful in reducing peak vGRF and only the higher cadence condition reduced braking impulse. These findings will inform clinicians who wish to use wearable devices for running gait modification to select injury-specific gait retraining cues.

**Level of Evidence:** Level 3

**Key Words:** running retraining, ground reaction forces, wearable devices
INTRODUCTION
High levels of certain metrics of ground reaction forces during running are associated with the development of common running related injuries. For instance, high average and instantaneous vertical loading rates (AVLR and IVLR, respectively) of the vertical ground reaction forces are associated with runners with tibial stress fracture,1,2 plantar fasciopathy,3 and patellofemoral pain.4 High braking impulses have been observed in runners with Achilles tendinopathy.5,6 Similarly, high levels of the peak vertical ground reaction force (peak vGRF) have been associated with knee pain7 and other running-related injuries.8 For instance, a high peak vGRF relative to measures of tibial bone strength was reported in runners with a recent history of tibial stress fracture.9 Notably, these running-related injuries are associated with a high rate of chronicity of recurrence.10–12 Runners with a past history of a tibial stress fracture have, for instance, a six-fold increased risk of sustaining a subsequent tibial stress fracture.10 Due to the high rates of re-injury, gait retraining has been proposed as a means to address lower extremity biomechanics in the hope to improve rehabilitation outcomes in runners.13

Recent advances in wearable technologies provide clinicians with the capability to assess running gait mechanics, cue changes in certain gait parameters, and then measure the runner’s adherence with the new running pattern during field-based runs.14 A commercially available running watch was recently found to be able to offer valid and reliable assessment of running cadence, ground contact time and vertical oscillation of a runner’s center of mass.15 Furthermore, Willy et al16 used a wearable device to cue a modest increase of 7.5% in running cadence, which reduced AVLR and IVLR at the conclusion of the eight-session gait retraining program. Monitoring of the participants’ running mechanics via the mobile device revealed that the runners successfully changed their running mechanics during the field-based retraining sessions and maintained these changes in the absence of feedback during the 30-day follow-up period.16,17 The results of these studies demonstrate the ability of clinicians to utilize widely available mobile technology to quantify and retrain certain running mechanics without the need for a fully instrumented gait laboratory.15

Besides reducing loading rates, a 5-10% increase in preferred running cadence (+5-10% over preferred) reduces the peak vGRF and braking impulse.16,18 However, there may be additional simple gait modifications that can affect ground reaction forces during running. Wille et al19 found that both cadence and magnitude of center of mass excursion are associated with vertical ground reaction forces and braking impulse. Thus, instructing a runner to reduce vertical oscillation of their center of mass may be a viable alternative cue to increased cadence if a reduction in loading rates, peak vGRF and braking impulse is desired. To date, it is not known which of these alterations is more effective at reducing lower limb loading patterns associated with running related injuries.

Therefore, the purposes of this study were twofold. First, to characterize the change in loading rates, peak vGRF and braking impulse in runners instructed to run with increased cadence or low vertical oscillation. Second, to determine whether changes in running mechanics predicted the changes in vertical loading rates, peak vGRF and braking impulse during the two running conditions. Understanding the relationship of gait modifications and lower limb loading can provide clinicians and patients with clinically applicable strategies that can be quantified and monitored using accurate and reliable wearable devices.

METHODS
Participants
A convenience sample of twenty active runners (running experience 11.5 ± 6.9 years and average running distance 37.3 ± 27.8 Km per week) was recruited to participate in this study. To be eligible, participants were required to be between the ages of 20-55, running at least 60 minutes per week and free of any injuries for the past 12 months. This study was approved by the University of Delaware Institutional Review Board and each participant gave informed consent prior to data collection.

Procedure
Participants wore a commercially available watch (fēnix2; Garmin Ltd, Schaffhausen, Switzerland), paired with a heart rate strap equipped with a tri-axial accelerometer (HRM-Run; Garmin Ltd) during
the experiment. This watch and associated accelerometer has previously been shown to be a valid and reliable assessment of cadence and vertical oscillation during running. Participants were asked to run on one of the two moving belts of an instrumented treadmill (Bertec Corporation, Columbus, OH).

Participants started running at a speed of 1.5 m/s. Running speed was increased 0.1 m/s every 10 seconds until participants reported reaching a comfortable self-selected running speed on the treadmill. Once participants reported a comfortable speed, they ran for one minute to become familiar with the treadmill and speed. If changes in speed were requested during the familiarization period, the speed was changed and another minute of familiarization was provided. Subjects continued to run after the familiarization period for one minute while data were acquired (baseline condition).

After the baseline condition, the first ten participants continued to run for two different thirty second running conditions at the same running speed as the baseline condition. In the first condition (high cadence), participants were asked to increase their running cadence. One of the investigators, a board certified orthopedic and sports specialist Physical Therapist, instructed participants to “Increase the number of times your foot hits the ground by 10%”. The investigator observed the participant and provided feedback prior to and during the condition. In the second condition (low oscillation), the investigator instructed participants to “keep their body as low to the ground as possible without slouching to reduce “bouncing” when running”. The investigator provided verbal feedback prior to and during the condition. Participants had a minimum of thirty seconds of running at their self-selected form before the second condition began.

Running spatiotemporal data (cadence, vertical oscillation, and ground contact time) were calculated using the proprietary algorithm of the Garmin Connect software and the average value for each condition was reported in step/min (cadence), centimeters (COM), and milliseconds (ground contact time).

Data analysis
Cadence, vertical oscillation, and ground contact time were calculated using the proprietary algorithm of the Garmin Connect software and the average value for each condition was reported in step/min (cadence), centimeters (COM), and milliseconds (ground contact time).

Visual3D software (version 5, C-Motion, Germantown, MD, USA) and a customized LabVIEW program (National Instruments, Austin, Tx) were used for the analysis of the GRF data. GRF data were filtered using a low-pass, fourth-order Butterworth recursive filter using a cutoff frequency of 50Hz. This filter cutoff frequency is routinely used when calculating loading rate of the vertical GRF during running, as described by Milner et al. A 20N threshold of the vGRF was chosen to identify footstrike and subsequent toeoff and accurate stance detection was confirmed with visual inspection of the individual trials. This stance threshold minimizes the chance of spurious event detection in running data collected on an instrumented treadmill. The GRF’s were then normalized to body weight (BW). Ten consecutive right stance phases were retained for calculation of discrete variables of interest.

The braking impulse was calculated as the time integral of the posterior-portion of the anterior-posterior GRF curves during stance and expressed in BW*sec. Next, loading rates of the vGRF’s were calculated.
AVLR (expressed in BW/sec) was calculated as the average slope of the middle 60% of the vGRF’s curve between footstrike and the vertical impact peak. In the case of an absent vertical impact peak, an index of 0.13 of stance length was used, as previously validated. During the same time window, IVLR (BW/sec) was calculated as the steepest part of the curve using the first central difference method. (Figure 1)

Statistical analysis

Reliability analysis

The reliability of the lower limb loading variables (AVLR, IVLR, braking impulse, and peak vGRF) was calculated in the subset of participants who ran two baseline conditions. Average values were compared between the two baseline conditions using Interclass Correlation Coefficient (ICC3,10). Pooled standard deviation was used to calculated the standard error of the measurement and minimal detectable change at the 95% confidence interval (MDC95).

Between-running conditions analysis

Running dynamic variables (cadence, vertical oscillation, and ground contact time) and lower limb loading variables (AVLR, IVLR, braking impulse, and peak vGRF) were compared between conditions (baseline, high cadence, and low oscillation) using a repeated measure analysis of variance (ANOVA). In case of a significant within conditions effect, Tukey Post-Hoc test with Bonferroni correction was used to measure differences between each running conditions. To assess clinical magnitude of change and to permit comparison with previous investigations, percent change, confidence interval, and effect size ($d$) were calculated. Two independent hierarchical linear regression models were used to predict the change of lower limb loading variables during the two running conditions (high cadence and low oscillation). The feedback given to participants focused on either increasing running cadence or decreasing vertical oscillation. Therefore, the change in cadence (for the high cadence condition) or the change in vertical oscillation (for the low oscillation condition) were entered first in the regression model. The change in secondary running dynamic variables (vertical oscillation and ground contact time, for the high cadence condition; and cadence and ground contact time for the low oscillation condition) were entered second in the regression model. This was done to understand whether the secondary variables would significantly improve the model prediction after accounting for the change in the primary variable. Statistical analysis was carried out using SPSS software (version 23, IBM, Amrok, NY, USA) and alpha level was set at 0.05.

RESULTS

Reliability analysis

All variables demonstrated excellent reliability, with ICC ranging from 0.985 to 0.999 (Table 1).

Between-running conditions analysis

Both spatiotemporal measures (Figure 2) and lower limb loading variables (Figure 3) were significantly different between running conditions (main effect

Figure 1. Calculation of vertical and braking and propulsive ground reaction force variables. A) average vertical loading rate (AVLR) and instantaneous vertical loading rate (IVLR) were calculated in the middle 60% of the vertical ground reaction force (GRF) curve between footstrike and the vertical impact peak. B) braking and propulsive impulse were calculated as the time integral of the respective portions of the anterior-posterior GRF curve.
of running condition, p < 0.001). The post-hoc analyses revealed that cadence increased 8.1% during the high cadence and 2.6% during low oscillation conditions compared to baseline, respectively. Moreover, cadence was higher in the high cadence condition compared to the low oscillation condition (MD: 8.7 step/min, p = 0.001). Vertical oscillation decreased 17.1% during the high cadence condition and 21.7% during the low oscillation condition compared to baseline, however no significant differences were observed between high cadence and low oscillation conditions (MD: 0.05cm, p = 0.999). Ground contact time decreased 4.7% during the high cadence condition compared to baseline; in contrast, ground contact time increased 3.5% during the low oscillation condition compared to baseline. AVLR significantly decreased 21.2% during the high cadence and 33.4% during the low oscillation conditions compared to baseline. IVLR significantly decreased 16.0% during the high cadence and 25.6% during the low oscillation conditions compared to baseline. Braking impulse significantly decreased
9.2% during the high cadence condition compared to baseline, but not during the low oscillation condition. Peak vGRF significantly decreased 3.5% during the high cadence and 11.4% during the low oscillation conditions compared to baseline. Furthermore, peak vGRF was significantly lower in the low oscillation condition compared to the high cadence condition (MD: -0.18 BW, p < 0.001). Mean change and effect sizes can be found in Table 2.

The increase in cadence during the high cadence condition significantly predicted the reduction of IVLR ($r^2 = 0.213, p = 0.041$) and braking impulse ($r^2 = 0.279, p = 0.017$). During the same high cadence condition, the changes in vertical oscillation and ground contact time were more predictive of the change of peak vGRF ($r^2$ change = 0.436, $p = 0.009$) compared to the change in cadence ($r^2 = 0.026, p = 0.493$). The decrease of vertical oscillation during the low oscillation condition was predictive of the reduction of peak vGRF ($r^2 = 0.748, p < 0.001$). During the same low oscillation condition, the change in cadence and ground contact time did not significantly increase the prediction of the regression model (Table 3).

**DISCUSSION**

Gait retraining can be an effective component of a comprehensive rehabilitation program for injured runners, yet it may be challenging to determine which gait parameters to target. Findings from the study revealed that cueing to either increase cadence or reduce vertical oscillation resulted in a decrease of AVLR and IVLR. These findings suggest that both methods of cueing may be used to manipulate spatiotemporal running parameters in patients with injuries related to changes in AVLR and IVLR, such as plantar fasciopathy or patellofemoral pain. Based on these data, cueing an increase in running cadence may be the preferred cue when the goal of the retraining is to decrease braking impulse. For instance, runners with Achilles tendinopathy were reported to run with ~9% greater braking impulse compared with healthy controls, which is equivalent to the reduction found in the present investigation during the high cadence condition. A recent report also found that increases in running cadence result in a small reduction in Achilles tendon loads. Taken together, these findings suggest that running with a modest increase in cadence may
be particularly helpful for runners recovering from Achilles tendinopathy.

The reductions in AVLR and IVLR noted with both the (-21.2--24.0%) high cadence and (-18.9%--16.8%) low oscillation conditions were associated with moderate to large effect sizes and likely clinically meaningful. Specifically, Milner and colleagues previously reported that runners with a past history of tibial stress fracture ran with AVLR and IVLR that were 16.0% and 13.9% higher, respectively, compared with healthy matched controls. Reductions in loading rates in the present study are consistent with other studies that cued 5-10% increases in running cadence, yet lower than interventions that cued a reduction in tibial shock (~ -32%), switching to a forefoot strike (~ -47%) or provided feedback on sound-intensity of footfalls (~ -35%). Future study is required to determine which of these interventions is most effective in reducing injury risk in runners who are thought to be prone to sustaining a tibial stress fracture.

Both methods of cueing also reduced peak vGRF from baseline, but the peak vGRF during the low oscillation condition was significantly lower than high cadence running condition. Further, the change from baseline of vertical oscillation predicted 46% of the variance of the change in peak vGRF during the high cadence condition (after accounting for the change in cadence); and 75% during the low oscillation condition. Previously, a low tibial bone strength relative to peak vGRF was observed in runners with a past history of tibial stress fracture. Due to reduction in both vertical loading rates and peak vGRF, cueing a reduction in vertical oscillation during running may have greater potential to reduce risk of a tibial stress fracture when compared with cueing an increase in running cadence. The kinematic strategies used to increase running cadence are well documented, but less is known for cues targeting vertical oscillation and is a topic for further development.

Table 2. Change from baseline of spatiotemporal and loading parameters during the high cadence and low oscillation running conditions.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Mean change (95% CI)</th>
<th>p Value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence, step/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>13.8 (10.3; 17.3)</td>
<td>&lt; 0.001</td>
<td>1.52</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>5.1 (1.6; 8.6)</td>
<td>0.004</td>
<td>0.38</td>
</tr>
<tr>
<td>Vertical Oscillation, cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>-1.7 (-2.2; -1.2)</td>
<td>&lt; 0.001</td>
<td>-1.2</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>-1.7 (-2.3; -1.1)</td>
<td>&lt; 0.011</td>
<td>-1.0</td>
</tr>
<tr>
<td>Ground contact time, ms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>-12.0 (-18.3; -5.6)</td>
<td>&lt; 0.001</td>
<td>-0.5</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>8.7 (0.3; 17.0)</td>
<td>0.041</td>
<td>0.3</td>
</tr>
<tr>
<td>AVLR, % BW/sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>-18.2 (-32.9; -3.5)</td>
<td>0.013</td>
<td>-0.8</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>-12.8 (-21.1; -4.5)</td>
<td>0.002</td>
<td>-0.4</td>
</tr>
<tr>
<td>IVLR, % BW/sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>-20.0 (-37.6; -2.47)</td>
<td>0.022</td>
<td>-0.7</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>-16.4 (-25.8; -7.00)</td>
<td>0.001</td>
<td>-0.4</td>
</tr>
<tr>
<td>Braking impulse, BW*’s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>-0.002 (-0.003; -0.001)</td>
<td>&lt; 0.001</td>
<td>0.6</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>0.001 (-0.001; 0.001)</td>
<td>0.999</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Peak vGRF, BW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cadence</td>
<td>-0.1 (-0.15; -0.01)</td>
<td>0.025</td>
<td>-0.3</td>
</tr>
<tr>
<td>Low oscillation</td>
<td>-0.3 (-0.35; -0.17)</td>
<td>&lt; 0.001</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

Abbreviation: CI, confidence interval; AVLR, average loading rate; IVLR, instantaneous loading rate; BW, body weight; vGRF, vertical ground reaction force.
1 Mean change calculated as (high cadence or low oscillation - baseline) running conditions
2 Tukey post-hoc with Bonferroni correction
3 Cohen d

Table 3. Regression analysis to identify predictors of loading based on the change from baseline of spatiotemporal variables during the high cadence and low oscillation running conditions.

<table>
<thead>
<tr>
<th>Regression steps</th>
<th>High Cadence</th>
<th></th>
<th></th>
<th></th>
<th>Low oscillation</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>R square</td>
<td>R square change</td>
<td>p-value change</td>
<td>R</td>
<td>R square</td>
<td>R square change</td>
<td>p-value change</td>
</tr>
<tr>
<td>AVLR</td>
<td>0.364</td>
<td>0.133</td>
<td>0.133</td>
<td>0.115</td>
<td>1 - Δ VO</td>
<td>0.169</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>2 - 1 Δ in VO and GCT</td>
<td>0.520</td>
<td>0.279</td>
<td>0.146</td>
<td>0.228</td>
<td>2 - 1 Δ in cadence and GCT</td>
<td>0.400</td>
<td>0.160</td>
</tr>
<tr>
<td></td>
<td>1 - Δ cadence</td>
<td>0.461</td>
<td>0.213</td>
<td>0.213</td>
<td>0.041*</td>
<td>1 - Δ VO</td>
<td>0.264</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>2 - 1 Δ in VO and GCT</td>
<td>0.628</td>
<td>0.395</td>
<td>0.182</td>
<td>0.122</td>
<td>2 - 1 Δ in cadence and GCT</td>
<td>0.387</td>
<td>0.150</td>
</tr>
<tr>
<td>Braking impulse</td>
<td>0.528</td>
<td>0.279</td>
<td>0.279</td>
<td>0.017*</td>
<td>1 - Δ VO</td>
<td>0.458</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td></td>
<td>2 - 1 Δ in VO and GCT</td>
<td>0.606</td>
<td>0.367</td>
<td>0.088</td>
<td>0.352</td>
<td>2 - 1 Δ in cadence and GCT</td>
<td>0.699</td>
<td>0.489</td>
</tr>
<tr>
<td>Peak vGRF</td>
<td>0.163</td>
<td>0.026</td>
<td>0.026</td>
<td>0.493</td>
<td>1 - Δ VO</td>
<td>0.865</td>
<td>0.748</td>
<td>0.748</td>
</tr>
<tr>
<td></td>
<td>2 - 1 Δ in VO and GCT</td>
<td>0.680</td>
<td>0.462</td>
<td>0.436</td>
<td>0.009*</td>
<td>2 - 1 Δ in cadence and GCT</td>
<td>0.872</td>
<td>0.760</td>
</tr>
</tbody>
</table>

Abbreviations: AVLR, average loading rate; IVLR, instantaneous loading rate; vGRF, vertical ground reaction force; VO, vertical oscillation; GTC, ground contact time.
* Significant R square change
When using cues for vertical oscillation, it is important that runners do not “slouch” or adopt a “groucho” running style.32 The use of commercially available wearable devices to measure spatiotemporal parameters of running is on the rise. These devices provide clinicians with reliable and accurate methods to track spatiotemporal running parameters.15 The results of this study show that changes in spatiotemporal running parameters measured with a wearable device can predict changes in lower limb loading measured with an instrumented treadmill. Clinicians may be able to utilize these devices to provide training feedback outside of a laboratory or clinical settings, and to monitor patients’ ability to alter gait mechanics and compliance with the prescribed alterations. Importantly, many wearable devices also record data on both running cadence and vertical oscillation during in-field runs, enabling clinicians to assess patient adherence during gait retraining interventions.14 Thus, both retraining cues tested in this study can be readily employed outside the clinic in a runner’s normal training environment.14 The customization of gait retraining to certain injury-specific mechanics and the ability to measure adherence with a retraining program may lead to enhanced outcomes for rehabilitation programs for the injured runner.

Although this study focused on running gait mechanics that can be identified using wearable devices outside of the confines of the laboratory, other studies have examined the change of gait mechanics on additional kinematic and kinetic parameters. An increase in cadence has been reported to be accompanied by reductions in peak hip adduction angle, hip external adduction and internal rotation moments,16,18,33 decrease in vertical impact loading rate,33 decreases in eccentric knee joint loads16,18,34,35 and patellofemoral and tibiofemoral joint loads.34,36,37 One of the temporospatial strategies associated with an increase in running cadence is a shortened step length,31,38 placing the initial loading closer to the runner’s center of mass18 and a reduction in stance time.31,38 Furthermore, increased leg stiffness has been reported when cadence is increased,38 primarily influenced by the reduced stance duration. Thus, it would be expected that our cohort increased leg stiffness in the high cadence condition due to the reduction in stance duration.38 During the low oscillation condition we found that participants adopted not only reduced vertical oscillation but also a 2.6% increase in cadence from baseline, resulting in a reduction in peak vGRF. These findings are consistent with a prior study that found an inverse relationship between vertical oscillation and cadence with peak vGRF during running.19 In contrast to the high cadence condition, cueing a reduction in vertical oscillation failed to reduce braking impulse. The unchanged braking impulse, coupled with the lower cadence in the low oscillation condition, is consistent with a slightly longer step length than the high cadence condition.18 Identification of the key biomechanical contributors for a change in AVLR, IVLR, and peak vGRF during the low oscillation condition requires a full analysis of kinematics and kinetics of the runners.

It is important to consider that this study was designed to measure the immediate effect of altering spatiotemporal parameters on loading variables. Adopting any new running mechanics may require short-term increases in metabolic demand. Large increases in running cadence39 or an exaggerated decrease in vertical oscillation40 have both been linked to an increase in the metabolic cost of running. The increase in metabolic demand may potentially negate the benefits associated with cadence or vertical oscillation manipulation, making it difficult for the runner to maintain the change in mechanics. However, Clansey and colleagues found no change in the metabolic demand of running when runners were cued to reduce tibial shock after an eight-session gait retraining program.41 Sustained changes of cadence and oscillation may produce different effects on metabolic measures. Future studies are required to determine the long-term effect on manipulating cadence or vertical oscillation on metabolic energy costs.

The current study is not without limitations including small sample size, lack of an injured population, and short duration of running. Future studies should look to assess full kinematic, kinetic, and loading rate parameters associated with changes in spatiotemporal measures over a longer duration of running during data collection, as well as in runners with a history of running-related injuries. Future
studies should also look to see long-term outcomes for changes in loading rates and metabolic demand.

CONCLUSION
Gait retraining cues for low vertical oscillation may be an effective alternative to increasing cadence for certain running related injuries. While both higher cadence and lower vertical oscillation resulted in reduced loading rates, there may be some advantages of low vertical oscillation in reducing peak vGRF and higher cadence in reducing braking impulse. Clinicians may look to use accurate and reliable wearable devices for gait retraining in a clinical setting to provide feedback to the patient and monitor their ability to modify running gait parameters.

REFERENCES


ABSTRACT

Background: Participation in high school cross-country continues to increase with over 492,000 participants during the 2016-17 cross-country season. Several studies have indicated a high incidence of running-related injuries (RRI) in high school cross-country runners. Risk factors for RRI can be divided between intrinsic and extrinsic risk factors. Intrinsic risk factors such as structural asymmetries have received less attention in recent years.

Purpose: The primary purposes of the current study were to (1) describe the prevalence of leg-length inequality among female and male high school cross-country runners, and (2) to determine whether leg-length inequality was associated with increased RRI in female and male high school cross-country runners.

Study Design: Prospective observational cohort study.

Methods: Three hundred ninety-three (222 males, 171 females) athletes competing in high school cross-country running were followed, prospectively. The runners’ right and left leg-lengths were measured with a standard cloth tape measure in a supine position. Incidence of low back/lower extremity RRI during practices or competitive events was monitored using the Daily Injury Report.

Results: A similar percentage of leg-length inequality greater than 0.5 cm was found among female (19.3%) and male (22.1%) runners. No statistically significant associations were found between leg-length inequality and (RRI) for female or male runners, with the exception that after adjusting for BMI, males with a leg-length inequality >1.5 cm were over seven times more likely to incur a lower leg RRI (Adjusted Odds Ratio = 7.47; 95%CI: 1.5, 36.9; p=0.01) than males with a leg-length inequality ≤0.5 cm. Side of RRI was not associated with side of longer limb length.

Conclusions: While leg-length inequality was not associated with RRI, in general, males with a leg-length inequality >1.5 cm were at greater likelihood of sustaining a lower leg RRI.

Level of Evidence: 2b

Keywords: Asymmetry, Leg-length, High school, Cross-country running, Prospective, Running-related injury
INTRODUCTION
Running continues to be a popular sport. According to RunningUSA, the number of running event finishers in the U.S. increased from an estimated 4,797,000 in 1990 to 17,114,800 in 2015. However, running has a relatively high incidence of lower extremity injury, with the incidence ranging from 17.9-79.3% based on the study design. Thus, understanding the relationship of factors related to the etiology of running-related injury (RRI) is an important focus of running research.

There is running-related literature that suggest that extremes of anatomic variation and malalignment may predispose runners and military populations engaged in running-related activities to musculoskeletal overuse injury.5-7 Of these, increased navicular drop and large quadriceps angle ([Q-angle] the angle formed between lines from the anterior superior iliac spine to the center of the patella, and from the center of the patella to the center of the tibial tubercle) or greater right-left Q-angle difference are considered risk factors. The literature regarding leg-length inequality as a risk factor for RRI is equivocal in adult competitive and recreational runners and military training populations.8-10 Several factors may contribute to the mixed results including differing study designs and measurement techniques, which do not allow direct comparisons among studies.8,10,22 Further, there is no consensus on a criterion that distinguishes a normal from an abnormal leg-length inequality.23

Over 492,000 female and male athletes participated in cross-country running in the United States during the 2016-2017 high school season.24 Recent studies of high school runners have indicated that the incidence of RRI ranges from 33% to 47% per season.25-28 Presently, there are no published prospective cohort reports that have provided an in-depth analysis on the relationship between leg-length inequality and RRI among high school runners. The author has previously reported on several risk factors in a large prospective observational cohort study.27 In this previous study, data was collected on leg-length but was not reported in-depth. Thus, the primary purposes of the current study were to (1) describe the prevalence of leg-length inequality among female and male high school cross-country runners, and (2) determine whether leg-length inequality was associated with increased RRI in female and male high school cross-country runners. Additionally, as the evidence for whether side of inequality is related to injury is mixed in adult running or military populations,17,18,29-35 side of inequality was examined to determine if the shorter or longer leg limb was associated with side of running-related injury in female and male high school cross-country. Further, as body mass index has been associated with RRI, particularly lower leg RRI, its influence on the relationship between leg-length inequality and RRI was assessed.

METHODS
Setting & Sample
The study prospectively followed 12 Washington State high school cross-country teams during a high school cross-country season. Four hundred twenty-one runners (186 females, 235 males), who competed on their teams during the high school cross-country season and were free of symptoms from any RRI at the time of the measurements, participated in the study. The study was approved by The University of Washington Human Subjects Division and the Seattle High School District. Parental consent and athlete assent was obtained for each subject prior to the baseline measurements. During the course of the season, 28 runners (15 females, 13 males) did not finish the season due to noninjury (i.e., stopped competing, dismissed from team). Thus, complete data for 393 runners (171 females, 222 males) were used in the final study analysis.

Data Collection
**Leg-Length.** Just prior to the season, the main investigator went to each high school at a scheduled meeting time and place to measure their school’s runners’ leg-lengths. The leg-length of both lower extremities for all runners were assessed with the subject in the supine position where each runner’s absolute leg-length was measured with a cloth tape measure from the anterior superior iliac spine to the medial malleolus and recorded in centimeters.41

**Pilot Reliability Study.** At a summer running camp prior to the season, the intrarater reliability for the leg-length measurements was established using a
convenience sample of 20 high school runners (10 females, 10 males; n = 40 limbs). The intrarater intraclass correlation coefficient (ICC 3,1) and standard error of measurement (SEM) value for the main investigator was 0.99 (1.05), and was similar for right and left limb lengths, indicating strong reliability and limited measurement error.

**Questionnaire.** At the time of the leg-length measurements, all subjects completed a questionnaire on baseline characteristics, which asked them to report their sex, age, height and weight.

**Running-Related Injury (RRI).** Prior to the season, the research team educated the runners to report any RRI symptoms to their coach. Additionally, each coach was trained in how to recognize common RRI symptoms among their runners and how to properly record them in the daily injury report (DIR) form. A RRI was defined as any reported muscle, joint, or bone problem/RRI of the low back or lower extremity (i.e., hip, thigh, knee, shin, calf, ankle, foot) resulting from running in a practice or meet that required the runner to be removed from a practice or competitive event or to miss a subsequent practice or competitive event. A day lost to RRI was any day in which the runner was not able or permitted to participate in an unrestricted manner. For each RRI, the coaches recorded the body location and side injured.

**DATA ANALYSIS**
Mean and standard deviations for age, height, weight, body mass index (BMI), and leg-length were calculated by gender to document the runner's personal characteristics. Statistical comparisons of baseline characteristics by gender were performed with the Student t test. The likelihood of a RRI by leg-length inequality was analyzed in four ordered categories (<0.5 cm, >0.5 cm to ≤1.0 cm, >1.0 cm to ≤1.5 cm, >1.5 cm) to evaluate a possible graded dose-response effect, using the leg-length ≤0.5 cm as the reference group. This latter group was chosen as the referent category because leg-length inequality in this range have been suggested as normal. Only the runner's initial RRI was used in all data analyses. Univariate odds ratios (ORs) with 95% confidence intervals (CIs) were used to compare initial RRI risks at different levels of leg-length inequality, comparing the cumulative incidence in an exposed group (>0.5 cm to ≤1.0 cm, >1.0 cm to ≤1.5 cm, or >1.5 cm), divided by the cumulative incidence in the baseline or referent group (≤0.5 cm). ORs and 95% CIs were also computed to assess whether side of RRI was associated with the side of longer leg-length. Univariate ORs and 95% CIs were then calculated to determine if RRI to specific lower extremity body parts were associated with leg-length inequality. Finally, multivariable logistic regression was used to calculate the adjusted ORs (AORs) and 95% CIs to assess the effect of body mass index (BMI) a potential confounding factor on the association between leg-length inequality and increased likelihood of RRI. An alpha level of 0.05 was used for all statistical analyses. All data were analyzed with SPSS (IBM Statistics SPSS 22.0, Armonk, NY).

**RESULTS**
Selected baseline characteristics of the 393 runners are presented in Table 1. Females and males were similar in age (p=0.82) (Table 1). While females were lighter and shorter than males, no significant differences were found in regards to BMI (p=0.34).

On average, females had significantly shorter (mean ± SD) right (87.38 cm ± 4.34) and left (87.39 cm ± 4.31) leg-lengths than males (92.98 cm ± 4.39 and 93.10 cm ± 4.42, respectively) (p<0.0001). The mean difference between right and left leg-lengths for females (0.34 cm ± 0.51) was not significantly different from the right and left leg-length mean difference for males (0.37 cm ± 0.57) (p=0.66). Females
(19.3%) and males (22.1%) had a similar percentage of leg-length inequality greater than 0.5 cm (Figure 1). Only one runner, a female, had a leg-length inequality value (2.5 cm) that exceeded 2.0 cm.

**RRI Incidence**

While 69 (40.4%) of the 171 female runners sustained at least one RRI, 79 (35.6%) of the 222 male runners experienced at least one RRI during the high school season. For females, the shin (42%) was the most common RRI site, followed by the knee (23%), hip (12%), and ankle (10%). For males, the knee (30%) was the body location most commonly injured, followed by the shin (22%) and ankle (13%).

**Likelihood of RRI by Leg-length Inequality**

Unadjusted and adjusted likelihood estimates of RRI in relation to leg-length inequality for females and males are presented in Table 2. For females and males, no statistically significant association was found between leg-length inequality and RRI. Similarly, when adjusted for BMI, no statistically significant relationships between leg-length inequality and RRI were found.

**Side of RRI by Limb Side**

While a slightly higher percentage of RRI occurred on the side of RRI on the limb with the greater leg-length (>0.5 cm) for males, the association was not statistically significant (p=0.68) (Table 3). Similarly, no association was found between side of RRI and longer limb side (>0.5 cm) for females (p=0.57). The relationship between leg-length inequality and body location injured is presented in Table 4.

**Likelihood of Injured Body Location by Leg-length Inequality**

After adjusting for BMI, males with a leg-length inequality >1.5 cm were over seven times more likely to incur a lower leg (shin/calf) RRI (AOR

![Figure 1. Distribution of leg-length asymmetry among high school cross-country runners (N=393).](image-url)
= 7.47, 95% CI: 1.5, 36.9; \( p = 0.01 \)) than males with a leg-length inequality \( \leq 0.5 \) cm. No statistically significant associations were found between leg-length inequality at other body locations for males or for females at any body location.

**DISCUSSION**

The findings of this study suggest that most female and male cross-country runners had symmetric right and left leg-lengths. While leg-length inequality was not associated with RRI, in general, males with a leg-length inequality > 1.5 cm were at greater likelihood of sustaining a lower leg RRI. Finally, a larger leg-length inequality was not related to side of injured limb for female or male runners.

Despite the use of leg-length inequality as a measure of structural abnormality to predict injuries in running and military populations, few studies have provided the prevalence of clinically-measured leg-length inequality data.\(^8\,10\,12\,18\) Furthermore, the difficulty in comparing the prevalence of leg-length inequality is that there is no widely accepted criterion value for what constitutes a large or excessive leg-length inequality for males or females, especially for adolescent runners. The criterion values reported in prior running and other athletic and military studies has varied from leg-length inequality of 0.5 cm to > 2.54 cm (> 1.0 inch).\(^8\,10\,12\,18\) Consistent with prior reports, few runners in this study had a leg-length inequality that would be considered excessive. Approximately 80% of the runners had a leg-length inequality less than 0.5 cm with a slightly higher prevalence of leg-length inequality i.e., > 0.5 cm, among the boy runners. Overall, using Reid and Smith's classification of bilateral discrepancy,\(^44\) all the runners' leg-length discrepancies would have been considered mild (i.e., inequalities less than 3 cm).

Consistent with prior studies,\(^8\,12\,21\) this study did not find a statistically significant relationship between leg-length inequality and overall RRI for high school cross-country runners. Noteworthy though was that for female and male runners, the findings suggested a pattern toward greater risk of RRI as the leg-length inequality increased. The non-statistically significant risk estimates may be partially due to the smaller number of runners with greater leg-length inequalities > 1.0 cm. Different measurement techniques have been used to examine the relationship between leg-length inequality and RRI. Only two studies were appropriate for direct comparison using the same measurement technique and criterions in this study,\(^10\,18\) with the findings in this study consistent with those reported by Rauh et al.\(^10\) but differing from those observed by Bennell et al.\(^18\) Comparisons with other studies that used the same measurement technique but did not specify a criterion were also equivocal.\(^11\,14\,15\,17\,19\,20\) The mixed findings indicate that further study is needed to determine if there is a more sensitive measurement technique or criterion, or both, that might be more valid to evaluate the risk relationship between leg-length inequality and RRI.

Several authors have reported associations between leg-length inequality and specific body locations (i.e., low back injury,\(^19\) ankle injury\(^19\)) or injury type

---

**Table 3. Cumulative incidence of RRI by side of RRI and side of greater-length inequality among high school cross-country runners.**

<table>
<thead>
<tr>
<th>Side of Greater Inequality (cm)</th>
<th>Side of RRI</th>
<th>Left Leg Injured</th>
<th>Right Limb Injured</th>
<th>Bilateral Limbs Injured</th>
<th>Lower Back Injured</th>
<th>Total Injured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Girls</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right limb &gt;0.5 than left limb</td>
<td>1 (4.5)</td>
<td>2 (13.3)</td>
<td>2 (6.7)</td>
<td>0 (0.0)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Right ≤0.5 to Left ≤0.5</td>
<td>20 (91.0)</td>
<td>10 (66.7)</td>
<td>22 (73.3)</td>
<td>2 (100.0)</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Left limb &gt;0.5 than right limb</td>
<td>1 (4.5)</td>
<td>3 (20.0)</td>
<td>6 (20.0)</td>
<td>0 (0.0)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td><strong>Boys</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right limb &gt;0.5 than left limb</td>
<td>5 (15.6)</td>
<td>2 (10.0)</td>
<td>3 (12.5)</td>
<td>0 (0.0)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Right ≤0.5 to Left ≤0.5</td>
<td>25 (78.1)</td>
<td>15 (75.0)</td>
<td>16 (66.7)</td>
<td>3 (100.0)</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>Left limb &gt;0.5 than right limb</td>
<td>2 (6.3)</td>
<td>3 (15.0)</td>
<td>5 (20.8)</td>
<td>0 (0.0)</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

*Number injured; RRI, running-related injury.*
In the current study, of the five body locations examined, only the lower leg, (shin/calf) was found to be associated with RRI among male runners with a leg-length inequality >1.5 cm. This finding differentiates from other studies that examined leg-length inequality and lower leg pain and found no significant relationship. It is possible that these previously cited reports did not find a relationship due to cross-sectional design, smaller samples, and populations studied (adult runners, female recruits). Even though the relationship between leg-length inequality and lower leg RRI was strengthened as the association remained significant after adjusting for body mass index, some caution is advised when interpreting the statistical significance of this finding as they are based on only seven male runners who had a leg-length inequality of >1.5 cm, of which three had a lower leg RRI. Still, the finding provides some support that greater malalignment of the lower extremities may increase the odds of a male high school runner incurring a RRI.

The evidence regarding whether the longer limb or shorter limb is at greater risk of RRI appears equivocal and has been primarily examined in adult populations. While several authors have reported the longer limb had a higher occurrence of RRI, others have indicated that the shorter limb was at more risk. The results of the current study indicate that the RRI did not always occur on the limb with the larger limb length. A possible reason why a side difference may not have been observed is that the cutpoint used may not have been observed is that the criterion used for RRI may have affected the ability to observe a right or left side greater side difference as over one-third (n=54) of the RRI were considered bilateral.

Several limitations of this study are noteworthy. The RRI collected in this study was based on self-reported RRI symptoms from the runners to the coaches or direct observation by the coaches if they suspected that a runner was experiencing a RRI symptom. The use of self-reported RRI data is a limitation as it relies on the accuracy of the athletes’ recall of their symptoms and the coaches’ ability to recognize and report the injury. Additionally, the classification of RRI was based on self-report and may have been subjective. Finally, the study was limited to male high school cross-country runners and may not be generalizable to other populations or body locations.

Table 4. Relationship between body location injured by leg-length difference among high school cross-country runners (N = 393).

<table>
<thead>
<tr>
<th>Leg length inequality</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0 to &lt;0.5</td>
<td>138</td>
<td>2 (1.5)</td>
<td>1.0(ref)</td>
<td></td>
<td>10</td>
<td>(7.2)</td>
<td>1.0(ref)</td>
<td></td>
<td>11</td>
<td>(8.0)</td>
<td>1.0(ref)</td>
<td></td>
<td>23</td>
<td>(16.7)</td>
<td>1.0(ref)</td>
<td></td>
<td>8</td>
<td>(5.8)</td>
<td>1.0(ref)</td>
<td></td>
</tr>
<tr>
<td>&gt;0.5 to ≤1.0</td>
<td>26</td>
<td>0 (0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>4</td>
<td>(15.4)</td>
<td>2.23</td>
<td>0.6-7.7</td>
<td>4</td>
<td>(15.4)</td>
<td>0.83</td>
<td>0.3-2.7</td>
<td>2</td>
<td>(7.7)</td>
<td>1.36</td>
<td>0.3-6.9</td>
</tr>
<tr>
<td>&gt;1.0 to ≤1.5</td>
<td>2</td>
<td>0 (0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>1</td>
<td>(50.0)</td>
<td>12.10</td>
<td>0.7-21.9</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>1</td>
<td>(50.0)</td>
<td>4.38</td>
<td>0.3-75.6</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
</tr>
<tr>
<td>&gt;1.5</td>
<td>5</td>
<td>0 (0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>2</td>
<td>(40.0)</td>
<td>2.67</td>
<td>0.4-17.7</td>
<td>1</td>
<td>(20.0)</td>
<td>4.06</td>
<td>0.4-40.7</td>
</tr>
</tbody>
</table>

Boys

<table>
<thead>
<tr>
<th>Leg length inequality</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
<th>N*</th>
<th>N (%)</th>
<th>AOR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 to &lt;0.5</td>
<td>173</td>
<td>3 (1.7)</td>
<td>1.0(ref)</td>
<td></td>
<td>11</td>
<td>(6.4)</td>
<td>1.0(ref)</td>
<td></td>
<td>18</td>
<td>(10.4)</td>
<td>1.0(ref)</td>
<td></td>
<td>15</td>
<td>(8.7)</td>
<td>1.0(ref)</td>
<td></td>
<td>12</td>
<td>(6.9)</td>
<td>1.0(ref)</td>
<td></td>
</tr>
<tr>
<td>&gt;0.5 to ≤1.0</td>
<td>30</td>
<td>0 (0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>1</td>
<td>(3.3)</td>
<td>0.48</td>
<td>0.1-3.9</td>
<td>2</td>
<td>(6.7)</td>
<td>0.65</td>
<td>0.1-3.0</td>
<td>3</td>
<td>(10.0)</td>
<td>1.27</td>
<td>0.3-4.8</td>
<td>3</td>
<td>(10.0)</td>
<td>1.51</td>
<td>0.4-5.8</td>
</tr>
<tr>
<td>&gt;1.0 to ≤1.5</td>
<td>12</td>
<td>0 (0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>2</td>
<td>(16.7)</td>
<td>2.95</td>
<td>0.6-15.2</td>
<td>2</td>
<td>(16.7)</td>
<td>1.71</td>
<td>0.3-8.5</td>
<td>3</td>
<td>(25.0)</td>
<td>3.52</td>
<td>0.8-14.8</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
</tr>
<tr>
<td>&gt;1.5</td>
<td>7</td>
<td>0 (0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>0</td>
<td>(0.0)</td>
<td>0.00</td>
<td>NA</td>
<td>3</td>
<td>(42.9)</td>
<td>7.47</td>
<td>1.5-36.9</td>
<td>1</td>
<td>(14.3)</td>
<td>2.20</td>
<td>0.3-19.9</td>
</tr>
</tbody>
</table>

N*, Number at risk for running-related injury; AOR, Adjusted Odds Ratio; CI, Confidence Interval; Ref, Reference group; NA, Not applicable.
a potential limitation as it may have resulted in an underreporting of RRI, possibly due to some runners feeling that their pain symptoms were not severe enough to report and continued running through the RRI and/or feared that they would be restricted from a practice or competitive event. Second, some coaches may not have reported all RRI into the DIR. However, coaches were trained in how to complete the DIRs and were contacted on a weekly basis to minimize underreporting. Thus, there was increased confidence that the coaches’ reporting of RRI events were reasonably reliable and accurate due to the training they received to recognize and report RRI.26,27,45

Several strengths of this study are also of note. This study found that leg-length measures for both limbs could be measured quickly and reliably on adolescent runners of both genders. The prospective design allowed the leg-length status of each runner to be established before RRI occurred, decreasing the likelihood of recall or measurement bias.42,46

Recommendations for Future Research
Further investigation into the relationship between running-related RRI and leg-length inequality is recommended, particularly prospective studies with larger male and female adolescent cohort sizes. This will increase the ability to better examine the effects on leg-length inequality and specific body locations by gender. It is also recommended that leg-length inequality data be grouped according to measured values so that the findings are more transferable for clinical interpretation.9,47 Finally, although preventive interventions using heel pad/lift or orthotics to correct leg-length inequality are commonly used, recent evidence examining their protective effectiveness in minimizing injury in running and other sport populations appears equivocal.48-53 While this particular study did not address whether heel pad/lift or orthotic use played a protective effect in RRI among high school runners with leg-length inequality, it still behooves future prospective studies to determine their role as an injury prevention measure.

CONCLUSION
The results of this prospective study of high school female and male cross-country runners indicate that leg-length inequality was not associated with RRI, with the exception that males with a leg-length inequality >1.5 cm were at greater likelihood of incurring a lower leg (shin/calf) RRI. Further, the shorter or longer limb was not associated with side of RRI. Given the lack of association between the injured side and the side of the leg-length inequality in this study, clinicians should give equal consideration to the long or short limb when evaluating the injuries of high school runners.

REFERENCES


ABSTRACT

Background: Foam Rolling (FR) has steadily gained in popularity as an intervention to increase range of motion (ROM) and reduce pain. It is believed that FR can remove restrictions due to fascial adhesions, thus improving ROM. FR has been proposed as a means to increase ITB length as a means to achieve these outcomes. Previous research has focused on the effects of FR over both muscle and fascia tissue together. However, no studies have examined the effects of FR over fascial tissue not containing muscle.

Purpose: The purpose of this study was to compare the acute effect of a single bout of foam rolling (FR) over the Iliotibial Band (ITB) compared to FR over the gluteal muscle group on hip adduction passive range of motion (PROM).

Methods: Twenty-seven participants were recruited for the study. Each participant performed three sessions: FR over tissue devoid of muscle, the ITB (PFR), FR over contractile tissue, the gluteal muscles (AFR), and a session without FR (control) in a randomized order. Hip adduction PROM was measured in a pre-post manner for each session.

Results: Results of the repeated measures ANOVA showed a significant interaction across session and time (F(2, 25) = 25.202, p < 0.001, ηp² = 0.502, 1 – β = 1.000). Post-hoc analysis showed the AFR post-test measure was significantly different from both control (p < 0.001) and PFR counterparts (p < 0.001). FR over the gluteal muscle group lead to a 14.8% improvement in hip adduction ROM, with PFR only a 2% improvement.

Conclusion: A single bout of FR over a myofascial group appears to increase PROM in healthy young adults, whereas FR over the ITB itself (primarily fascial tissue) does not. This suggests the conventional theory behind FR may need to be reevaluated.

Level of Evidence: Level 1B, laboratory study, repeated measures design

Key Words: Fascia, foam rolling, iliotibial band, Ober’s Test, range of motion

CORRESPONDING AUTHOR

MacGregor Hall
Beleura Health Solutions
945 Napean Hwy
Mornington, Victoria, 3931 Australia
Tel: 614-68-995-028
Fax: 613-5976-2599
E-mail: macatcoastal@gmail.com

1 Beleura Health Solutions, Mornington, Victoria, Australia
2 Department of Kinesiology, Coastal Carolina University, Conway, South Carolina, USA

Conflict of Interest:
The authors have no conflicts of interest to declare.
INTRODUCTION

Foam rolling (FR) has gained favor as an adjunct to manual therapy to increase range of motion (ROM) and improve outcomes with regard to pain. FR over the iliobial band (ITB) is a popular adjunct in treatment for patellofemoral pain syndrome, runner's knee and hip bursitis. More recently, FR has become common practice for the general population, adopting the technique before training and exercising as a means for enhancing ROM, as self-massage, as an adjunct to warm-up, and to reduce pain associated with muscle soreness.

FR is proposed as a method to remove restrictions in ROM due to fascial adhesions, despite limited evidence that FR is capable of achieving this outcome. Evidence for FR having an effect on adhesions is limited to studies assessing changes in ROM. However, these studies have focused FR over myofascial tissue, with a significant component of the tissue being muscle, or "active" tissue. Significant skepticism remains as to whether or not FR therapy can generate sufficient pressure to remove any restrictions in ROM that may exist in passive, or non-contractile tissues, such as the ITB. Other fascial release techniques have limited evidence. Rolfing is a technique that combines deep manual therapy with active movement. Rolfers posit that Rolfing improves ROM of the fascia. However, Rolfing under anesthesia has been shown to have no change in tissue length.

The ITB is comprised exclusively of dense connective tissue, and is devoid of muscle fibers. Its anatomical origin arises from the proximal end of the tendons of the tensor fasciae latae (TFL) and gluteus maximus muscles, converging into the proximal bands. It continues down the lateral femur and crosses the knee joint where most of its fibers insert on Gerdy's tubercle. Some of the ITB's deeper fibers insert on the linea aspera of the femur, while some distal superficial fibers blend with the lateral retinaculum of the patella. The TFL acts as a lateral hip stabilizer and assists the gluteal muscle group during hip extension.

Functionally, it is believed that the orientation of fascial fibers allow for reduced activity from the gluteal muscles to maintain hip stability due to the intrinsic strength of the ITB, the orientation of the fibers and the relatively low ground reaction forces that occur during a static weight-bearing position. As such, the ITB serves to reduce work required by the gluteal muscles during gait, and accepts load directly.

The gluteal muscle group is traditionally divided into three distinct muscles: the gluteus maximus, gluteus medius and gluteus minimus. However, this division has been called into question, as Flack et al found poor evidence for compartmentalization based on fascial separation, innervation and individual function. Collectively, the gluteal muscle group forms a large, fan-shaped muscle whose fibers converge on the greater trochanter of the femur deeply and blend with the ITB superficially. The contractile elements of the muscle fibers pull on its fascial fibers, including those of the ITB, to generate extension, abduction and external rotation of the hip.

FR over the posterior lateral hip area cannot be specific to a single type of tissue. Indeed, there is a non-contractile (fascia) tissue within this area which is similar histologically to the fascia found in the ITB. However, the primary difference between the fascia of the ITB and that of this gluteal muscle group is the significant presence of contractile tissue. As such, this area has more neurological and proprioceptive input than the ITB, as the gluteal muscles are supplied with both sensory neurons in the form on Pacinian corpuscles and Merkle's discs and mechanoreceptors. Further, the gluteal muscles are capable of actively alternating length via efferent input and GTO and muscle spindle activity. However, the ITB is unable to alter its length, as it is primarily the tendinous fascia from the tensor fascia latae and is largely devoid of motor neurons, therefore any changes in ITB ROM from FR are likely to be due to muscular adaptions, rather than the removal of mechanical restrictions due to fascial adhesions, as popular theory suggests. Previous FR studies have documented increases ROM when applying this intervention over regions of the body containing muscle. The acute effect of FR over non-muscle tissue on ROM is unknown. Therefore, the purpose of this study was to compare the acute effect of a single bout of FR over the ITB compared to FR over the gluteal muscle group on hip adduction passive range of motion (PROM).
METHODS

Subjects

Twenty-seven (14 female, 12 males) healthy adults volunteered for this study. Exclusion criteria included prior lower limb or low back injury, currently participating in a stretching program, or any use of foam rolling within the previous six weeks. One participant was eliminated from the study due to failure to comply with the testing protocol. Mean ± SD for age, height, and weight for female subjects were 21.07 ± 1.141 yrs, 166.36 ± 7.110 cm, and 68.00 ± 10.53 kg, respectively. Mean ± SD for age, height, and weight for male participants were 21.50 ± 1.243 yrs, 171.92 ± 6.640 cm, and 79.682 ± 19.573 kg, respectively.

Testing Procedure

Each participant completed three sessions (control, active foam rolling (AFR), and passive foam rolling (PFR). Sessions were randomized by numbered containers selected by the author, and concealed until all interventions were assigned. Each session was scheduled one week apart at the same time of day and location. Prior to participation, each participant completed an informed consent and health history questionnaire. All procedures were approved by the Coastal Carolina University Institutional Review Board, approval code #2016.41. The rights of all subjects were protected.

During the control session, each participant performed a five-minute warm-up by pedaling continuously at 50 rpm (50 Watts of resistance) on a cycle ergometer (Monark Ergomedic 828E, Vansbro, Sweden). Seat height was set to allow for a 5-10° bend in the extended knee. The same seat height was used for each session. Immediately following the warm-up, each participant had their passive hip adduction ROM assessed bilaterally using the modified Ober test. The Ober test has been shown to be a reliable test to assess hip adduction ROM24,25 and therefore able to identify restrictive ROM of abductive tissues, such as the ITB and gluteal muscle group.26 With the participant in a side-lying position on a padded treatment table, both anterior superior iliac spines (ASIS) of the pelvis were maintained in a perpendicular to the ground and stabilized by the examiner using a hand on the lateral hip. The non-test leg was flexed at the hip and knee so that it did not inhibit test leg adduction. The test hip was then passively adducted to the end of its ROM with the knee flexed to 90°. A digital torpedo level (Model 320.48295, Craftsman) with an accuracy of ± 0.1° was placed just proximal to the lateral femoral condyle and in line with the femur. Each leg was assessed twice with the highest reading being recorded for each leg. The leg with the smaller ROM as measured by the modified Ober test was used for the intervention leg for all three sessions. This leg was chosen as the test leg because a principle aim of FR is to improve ROM.

For the control session, the participant sat in a chair for three minutes prior to having the modified Ober test performed in the same manner as previously described for the post-test result. The procedure for the AFR and PFR sessions were the same as the control session with the exception of foam rolling being performed instead of resting for three minutes. For the AFR session, participants foam rolled over the gluteal muscle group for the hip that had the least amount of flexibility as determined during their first session. Participants sat on a 36 x 6 inch round, high-density ethylene vinyl acetate foam roller on the floor with their feet flat on the ground. The non-test leg was placed in a figure-four position, with the ankle placed just proximal to the opposite knee. The participant’s hand on the test side was placed behind the participant on the floor for balance (Figure 1). Participants rolled the over gluteals, moving in a caudal-to-cephalad direction from the posterior superior iliac spine (PSIS) to the gluteal fold. Using a metronome to keep pace, participants foam rolled

---

Figure 1. Foam rolling the gluteal muscle group.
at a rate of 30 rolls per minute with rolling from the gluteal fold to the PSIS and back to the gluteal fold counting as one roll. Three sets of 30 seconds of foam rolling were completed with 30 seconds of rest between each set. For the PFR session, participants foam rolled over the ITB instead of the gluteal muscle group. During this session, the participant was in the side-lying position with the test leg bearing the weight of the foam roller. The ipsilateral hand was placed on the ground under the shoulder for support, and the contralateral leg was placed in front of the test leg with the foot flat on the floor for balance (Figure 2). Participants rolled in a caudal-to-cephalad direction from the greater trochanter to the lateral femoral condyle of the femur. Three sets of 30 seconds of foam rolling with 30 seconds of rest between sets were performed at the same pace as the AFR session. The post intervention Ober test was performed immediately after completing each FR session, and measured as previously described.

Statistical Analysis
A two-way (session x time) Repeated Measures Analysis of Variance (RMANOVA) was used to assess statistical differences in ROM within and across each session. If the results of the RMANOVA were significant, paired t-tests using a Bonferroni adjustment was conducted as a post hoc analysis. Intrarater reliability was assessed across all three pretest measures using intaclass correlation coefficient (ICC) model 3,1 according to Shrout and Fleiss. All statistical analyses were performed using SPSS (version 22, IBM Corporation, Armonk, NY). The alpha level was set to 0.05. Results are reported as means ± SD.

RESULTS
Table 1 provides the hip adduction ROM measures from each session. AFR resulted in a 14% improvement in modified Ober measurement, whereas PFR saw a 1.1% improvement in modified Ober PROM. Controls had a 2% decrease in modified Ober testing. Results from the two-way RMANOVA revealed a significant interaction for session and time ($F(2,25) = 25.202, p < 0.001, \eta_p^2 = 0.502, 1 - \beta = 1.000$). Preliminary analysis of a one way RMANOVA was performed on pre-test measurements across sessions. There was no significant difference across pre-test measurements ($p > .05$). The ICC for the pretest measurements was 0.815 (95% confidence interval = 0.680, 0.905) indicating a high level of reliability. Post hoc analysis showed that the post-test measurements for the AFR session was statistically significantly greater than the control ($p < 0.001$) or PFR post-test measurements ($p < 0.001$). There was no significant difference in post-test measurements between control and PFR ($p = 0.188$).

DISCUSSION
The results of this study suggest that foam rolling over the ITB directly has no immediate benefit in

| Table 1. Pre-test and post-test hip adduction ROM, presented as Mean (SD). All measurements are in degrees. Negative numbers represent degrees below horizontal (0°). |
|---|---|---|
| Session | Pretest | Posttest |
| Control | -26.0 (5.1) | -25.5 (5.4) |
| AFR | -25.9 (5.3) | -29.6 (5.5)* |
| PFR | -25.8 (5.8) | -26.1 (5.8) |

AFR = Foam Rolling over the gluteal muscles, PFR = Foam Rolling over the ilio-tibial band
* Represents a statistically significant different from Control and PFR post-test measurements, $p<0.05$. 

Figure 2. Foam rolling for the iliotibial band.
increasing hip adduction ROM, as measured by the modified Ober test. However, FR over the gluteal region resulted in an immediate, statistically significant increase in hip adduction ROM.

The clinical significance of these changes in ROM are less well defined. Generally, changes in outcomes that are considered important are determined by the patient or the clinician, so any changes that exceed these expectations are considered significant.29 No standardized value for improvement in hip adduction ROM is currently available for clinical purposes. However, some have suggested that using standard deviation (SD) within a study can be used to determine clinically significant changes. Wyrwich30 reported 2.3 times SD would ensure clinical significance. Using this measure, AFR needs an improvement of 4.1° to approach clinical significance (the current study saw a change of 3.5°), whereas PFR needed 6.4° to ensure clinical significance (the current study only saw a change of 0.3°).

The results of the effects of AFR are consistent with other findings on FR over muscle-fascia tissue in that a statistically significant increase in ROM was observed. However, AFR resulted in an improvement of 14.3% in Ober test ROM, more than the 6.2%,29 4.2%,3 and 2%,31 ROM improvements found in other studies. Further, previous studies have only looked at the effects of FR over tissue that contains both muscle and its surrounding fascia.1-3, 33-35 This study has included the effects of FR over the ITB, a tissue composed primarily of connective tissue, devoid of any significant contractile component.

The current findings may be due to differences in pressure impulse, as the target tissue in the AFR group in the current study (the gluteal muscles) is much smaller in length than the target tissues in other studies.2,3,33,34 therefore in order to maintain pace with the metronome, subjects would have to roll slower than if rolling larger tissues at the same pace, resulting in a greater impulse moment on the tissue.

This study is consistent in design with previous studies on the effects of FR. Precautions were taken to isolate the target tissue of the gluteals or ITB. FR pacing was similar to other studies4, 33, 35-37 as well as in frequency and duration dosages.31,35,38 Therefore, the significant difference in ROM in the current study is likely due to other factors.

There are three theories proposed to explain observed changes in ROM after FR. Most prevalent is that myofascial adhesions develop over time, resulting in reduced ROM.40 Advocates of FR propont that FR is able to reduce fascial adhesions,41 thus improving ROM. Second, alterations in blood flow and vascularization within the fascia are shown to change as a result of FR, which may lead to reduced neural inhibition.42,45 Finally, there is a proposed neurological mechanism that involves the facilitation of muscle relaxation / inhibition, which would occur to a greater degree in myofascial tissue than fascia alone.15

Myofascial Adhesions

Fascia is made of connective tissue, mostly collagen and elastin.21 It does have Pancinian corpuscles and Ruffini nerve endings, suggesting it may play a role in proprioception. It also has free nerve endings and chemoreceptors, suggesting it can be a source of pain.13, 44 Histologically, fascia is composed primarily of fibroblasts, which maintain the extracellular matrix (ECM).21, 45 There is some speculation that sustained static positions cause a colloidal, congealing of the fluid within the fascial fibers, within the gel-matrix - described as ‘fuzz’ by Hedley.46 It is postulated that this stiffening or thickening (fuzzing) of the colloidal gel results in a restriction of ROM and altered lines of pull on muscle action and restricted motion, termed “fascial adhesions”.46

The results of the current study suggest that if any fascial adhesions existed in the sample pool, FR over myofascial tissue would improve ROM, whereas an acute bout of FR over fascia alone would not acutely change ROM. However, the long-term effects of FR may warrant further research. Since the population for this study were devoid of any lower limb injuries, so the presence of fascial adhesions seems unlikely. Different results may be found in a pathological population.

Reese and Bandy25 found normative Ober measurements of -18.9° (+/-7.6°), and Hudson and Darthus47 reported Ober to be 20.9° (+/-4.3°) in healthy subjects. As the current sample had significantly more
hip adduction ROM on Ober test, mean = -26.0º (SD = 5.1), it is possible that the sample population lacked fascial adhesions, thus the possibility of detecting significant changes due to any effect on fascia was limited. The sample pool was composed primarily of kinesiology students, who may have an inherently healthier profile than the general population, as they may be more active and health conscious due to the nature of their studies. In addition, we cannot rule out possible subtle differences in stabilization of the lateral hip during the modified Ober since we did not measure the angle created by the lateral hip and table. Regardless, the significant change in PROM present after AFR suggests that other mechanisms may need to be considered.

**Alterations in Vascularity**

There is some support for the suggestion that foam rolling can improve blood supply to an area by improving the elasticity of the arteries.⁴²,⁴³ Neo-vascularization in connective tissue has been postulated as a source of pain in patellar mal-tracking⁴⁵ and some tendinopathies.⁴⁹ This in turn may lead to guarding and pain inhibition, reducing ROM. Repetitive foam rolling may damage new vessels and nerves that form during the neo-vascularization phase of the formation of collagen as fascia tissue proliferates, as has been shown to be the case in patellar mal-tracking⁴⁵ leading to reduced pain and possibly less pain inhibition. As this study only exposed the area to FR for one session, the dosage required to elicit these proposed changes may have been inadequate to measure the effect of any alterations in vascularity or perfusion due to FR. Further, as injury to the lower limb was an exclusion criteria in this study, it is possible that the subject pool lacked any vascular adhesions for FR to act upon, explaining the lack of significant findings in the PFR group. Outcomes in a clinical population may yield different results.

**Neural Plastic Changes**

Recent evidence suggests that the changes in ROM observed as a result of FR are due to neural excitability and improved facilitation of muscle tissue.⁷,¹³ GTOs are located in connective tissue.⁵⁰ GTOs respond to slow stretch – which is simulated by FR – by reducing their firing rate, thus reducing tonus in adjacent muscle. This “softening” may account for a perceived increase in joint ROM.¹³

Effects on Ruffini corpuscles have been suggested as a cause for the changes due to FR.¹³ These slow-adapting receptors could alter their neural transduction with a sustained stretching stimulus. With reduced transmission to the brain, there is less for the brain to perceive, resulting in less efferent activity to target muscles, and therefore an overall improved neural effect on tissue ROM.⁵¹ This in turn could result in improved neuromuscular activity. Fascia does contain some contractile capacity much the same way as smooth muscle does.⁵² While it is conceivable that reduced neural input to the smooth muscles in the ITB may result in increased ITB length, this was not shown in this study. Given the chronic exposure to abnormal forces required to form the adaptive changes found in the ITB in overuse injuries, it is unlikely that a single bout of FR would produce the stimulation necessary to promote cellular remodeling. However, the effects of repeated exposure to non-contractile tissues has not been explored in the literature and warrants future investigation.

Cavanaugh et al⁷ suggested that a neural inhibition response occurs after FR that may reduce pain perception. It is possible that due to the increased afferent neural environment of the myofascial tissue compared to the ITB, a reduction in inhibitory neural drive allows for improved ROM in the AFR population. Similar improvements in pain tolerances have been reported by Aboodarda et al.⁶ The Ober test uses passive ROM to determine end-range, rather than pain, subjects may have experienced an increase in pain as the limb approached end-range. After FR, improvements in pain inhibition may account for the observed changes.

**Limitations to the study and Future Considerations**

While the AFR session had a significant increase in hip adduction ROM, PFR did not have a similar effect. However, this subject population had good initial flexibility, mean = -26.0º (SD = 5.1). It is possible that a population with lower initial Ober ROM would yield different outcomes. The traditional theory behind FR’s mechanism of action on connective...
tissue is an improved compliance of fascia, however it is difficult to ascertain if such adhesions exist. Given the health status of the test population, it is unlikely that these adhesions were present in any subjects.

Indeed, only one study confirms fascial adhesions with imaging findings. Baumann et al. correlated contrast-enhanced MRI findings of increased tissue thickness and signal abnormalities with clinical findings (loss of ROM, weakness, pain and skin thickening) and biopsy results to fascial adhesions. However, the subjects in their population had an autoimmune trigger to the adhesions. These findings likely do not apply to the general population.

It is possible that the intensity, cadence or duration of the sessions were insufficient to elicit detectable changes in fascial tissue. MacDonald et al. examined up to 20 minutes of FR on ROM of the knee. However, the outcome (6% increase in ROM) was no better in ROM changes than shorter duration studies. Sullivan et al. used a massage roller at a cadence of 120 bpm and found a 4.3% improvement in sit-and-reach. However, the sit-and-reach is an assessment of neural length and its validity as a hamstring assessment tool is less reliable than other outcome measures for the hamstring. Further, massage roller may not be the same as FR in regards of force application or impulse. The current study used subjects’ body weight as the intensity of the pressure elicited on the roller. As the pressure was not standardized otherwise, it is possible that those with greater body weight or less fat mass could elicit greater force over the tissue, generating greater effect from FR. Greater adipose dissipate some of the pressure exerted on the underlying tissues. Further, pain from FR over the ITB could cause some pain inhibition not seen when addressing the gluteals using FR. However, body weight is a common force used in other studies.

This study only included one follow-up measurement on the Ober test, immediately post FR or control. Markovic found the effects of FR on ROM can last as long as 24 hours post rolling. While it is unlikely that any increases in ROM from PFR are likely to be observed later, the duration of AFR would be useful to know. Further, the effects of repeated FR could show different results. Knowing the duration of effect would be beneficial in determining protocol for repeated FR.

There are several models of foam rolling devices available on the market. This study used a smooth, 36 x 6-inch round, high-density ethylene vinyl acetate foam roller for all sessions. Other studies have found ROM improvements using textured foam rollers, roller massage machines and manual roller massagers, although with varying degrees of improvement. However, to date no study has examined the effectiveness of different modalities within groups.

The percentage change in the AFR group in this study is greater than those found in other studies. This may be due to the increased impulse of the FR over the tissue. The gluteal is smaller in longitudinal length than that of the muscle groups used in other studies. As such, in order to maintain a cadence of 30 rolls per minute, subjects would have rolled at a slower velocity to maintain cadence over the smaller distance, resulting in a greater overall contact time and possibly greater effects from the FR. This difference may be due to greater impulse over the tissue, the FR composition or a combination of the two.

Further study on the effects of repeated exposure to FR on both fascial and myofascial tissue is logical, especially in this region, given these findings. Additionally, the effective of various durations, cadences and repetitions of FR warrants investigation. Current dosages appear to be consistent within the literature, however, justification for these dosages appear to be lacking. Finally, comparison of the effects of foam rollers and rolling devices is lacking within the literature, and warrants further investigation.

**CONCLUSION**

The results of the current study suggest that foam rolling over the gluteal muscles is an effective means to significantly improve an immediate measure of passive hip adduction ROM. This is in accordance with other studies on the effects of FR on muscle tissue length. However, a single bout of foam rolling over the ITB did did not produce a significant increase in passive hip adduction ROM. It is unclear what effects repeated exposure to FR on the ITB may have on Ober test and ROM in general.
REFERENCES


ABSTRACT

Background: Kinesiology Tape (KT) is widely used in sports rehabilitation and by those performing physical activity, however, there is no consensus in the scientific literature about its effectiveness on performance, strength or muscle activation.

Purpose: The purpose of this study was to measure the acute effects of KT in static rest, and during knee extension maximal voluntary isometric contraction (MVIC) performance in resistance trained men.

Study Design: Observational, descriptive, comparative.

Methods: Eighteen young, healthy, trained males (age: 25±6 years, height: 176.0±5 cm, and mass: 81.8±8.0 kg) volunteered to participate. Initially, they were in a relaxed sitting position of 90 degrees knee flexion with their limb supported by the machine lever arm to measure passive tension of the tissues of the knee joint. Then, they performed three MVIC trials of five seconds each with a three-minute rest between trials, in four randomized experimental conditions, with 10-min rest between conditions: (a) control, no taping; (b) Knee Sleeve; (c) KT; and (d) sham. During all MVICs, peak force, impulse, and muscle activation of the vastus lateralis (integrated electromyography [IEMG] and median frequency) were measured.

Results: Repeated measures ANOVAs revealed no statistical differences between conditions for passive tension \((p>0.05)\), peak force \((p>0.05)\), impulse \((p>0.05)\), IEMG \((p>0.05)\), or median frequency \((p>0.05)\).

Conclusion: KT does not influence passive tension during static position at 90 degrees of knee flexion. KT does not affect quadriceps activation or force production during a maximal voluntary isometric contraction in the same position.

Level of Evidence: 3a

Keywords: Electromyography, force, kinesiology tape, muscle performance, quadriceps.
INTRODUCTION
Kinesiology Tape (KT) is a method introduced by Kase et al.\textsuperscript{1} in 1973, and has been widely used in sports rehabilitation and by those who participate in physical activity. It has been claimed that KT might enhance normal functional movements, decrease pain, and decrease swelling,\textsuperscript{2} additionally, several researchers have investigated its use to increase performance, strength or muscle activity.\textsuperscript{3-24}

Previous authors have attempted to verify the effect of KT on force,\textsuperscript{6,9,11,12,18,21,25-27} torque,\textsuperscript{4,5,10,17,28} and muscle activation.\textsuperscript{6,18,22-24,29,30} Some researchers have observed a significant increase in a specific performance,\textsuperscript{3-21} and muscle activity,\textsuperscript{6,22-24} while others have shown no significant effect.\textsuperscript{29-38} The aforementioned studies illustrate that there is no consensus in the scientific literature about the efficacy of KT in performance, strength and muscle activation. Furthermore, these studies provide conflicting results due to differences in population as well as methodology (inclusion of the sham or control group), KT application (direction, pattern of application, tension), muscles evaluated, and tests performed. Additionally, to the best of authors’ knowledge, no study has verified the passive tension provided by KT, which might explain improvements in total amount of force that is produced by subjects in some studies. In this case, the passive tension of the KT is the additional force produced by the material proprieties, and might be added to the contractile force to produce improvement in performance.\textsuperscript{39-42} Therefore, the purpose of this study was to measure the acute effects of KT in static rest, and during knee extension maximal voluntary isometric contraction (MVIC) performance in resistance trained men. The null hypotheses of the present study are: (1) KT will not affect passive tension during static rest; and (2) KT will not affect muscle activation or force output during an MVIC.

METHODS
Subjects
The number of participants was determined by using a pilot study conducted previously, with individuals with the same characteristics used in the present study, based on a significance level of 5% and a power of 80% derived from the peak force on MVIC test.\textsuperscript{43} Eighteen young, healthy, resistance trained males (age: 25±6 years, height: 176.0±5 cm, and total body mass: 81.8±8.0 kg) volunteered to participate. They had 5±2 years of experience resistance training, at least three times a week. They had no previous surgery on their lower limbs (specifically in the knee joint) and no history of injury with residual symptoms (pain, “giving-away” sensations) in the lower limbs within the prior year. This study was approved by the Methodist University of Piracicaba research ethics committee (#65/2015) and all subjects read and signed an informed consent document.

Procedures
Prior to data collection, subjects were asked to identify their preferred leg for kicking a ball, which was then considered their dominant leg.\textsuperscript{44} All subjects were right-leg dominant. Subjects attended one session in the laboratory, and they reported to have refrained from performing any lower body exercise other than activities of daily living for at least 72 h prior to testing.

Subjects performed a general warm-up of lower body cycling for five minutes at a cadence of 70 rpm at one kilopound prior to testing. Dominant leg knee strength was measured with MVIC testing, completed while seated on a leg extension machine (Leg Extension Machine, Riguetto, Brazil), and positioned at 90° of knee flexion with the limb (lateral femoral condyle) in alignment with the mechanical axis of the equipment. Hips were positioned at 90° of hip flexion, arms crossed over their chest, and trunk was secured to the chair by belts. A strap was also placed across their pelvis to minimize hip movement. The machine lever arm was connected perpendicularly to a load cell (EMG832C, EMG system do Brasil, São José dos Campos, Brazil), which was interfaced with a computer for recording, sampling at 2 kHz. Then, a specific warm-up of five submaximal unilateral isometric knee extension contractions were performed. After a 10-minute rest, all subjects performed three MVIC trials of five seconds each with three-minute rest between trials. Prior to MVIC measurement subjects were required to remain relaxed with their limb supported by the machine lever arm, and the force measured in this condition was considered the passive tension of the knee joint. The passive tension was measured in all
conditions. After that, all subjects were instructed to initiate each MVIC as hard and fast as possible. Consistent standardized verbal encouragement was given during all tests. All tests were performed at the same hour of the day, between 9 AM and 12 PM, and by the same researcher.

**Surface Electromyography (sEMG):** Participants’ skin was prepared by shaving hair at the site of electrode placement and cleaned with alcohol. Bipolar passive disposable dual Ag/AgCl snap electrodes were used which were 1-cm in diameter with 2-cm center-to-center spacing. They were attached on the dominant limb over the longitudinal axis of the Vastus Lateralis (VL) at two thirds the distance between the anterior superior iliac spine and the superior aspect of the lateral side of the patella, according to the SENIAM/ISEKI protocol. The sEMG signal of the VL was recorded by an EMG acquisition system (EMG832C, EMG system do Brasil, São José dos Campos, Brazil) sampling at 2KHz using a commercially designed software program (EMG system do Brasil, São José dos Campos, Brazil), and synchronized with the load cell. The sEMG activity was amplified (bi-polar differential amplifier, input impedance = 2MΩ, common mode rejection ratio > 100 dB min (60 Hz), gain x 20, noise > 5 μV), and analog-to-digitaly converted (12 bit). A ground electrode was placed on the right patella.

All MVICs and sEMG data were analyzed with a customized Matlab routine (MathWorks Inc., USA). MVIC data were filtered using a fourth-order Butterworth filter with a 10 Hz cutoff frequency. Peak force was defined as the maximal value of each MVIC, after removing the passive tension of the knee joint. Impulse was measured as the integrated MVIC during the first two-seconds of the contraction. For the temporal analysis, the digitized sEMG data were band-pass filtered at 20-400 Hz using a fourth-order Butterworth filter with a zero lag. For muscle activation, the root mean square (RMS) (150ms moving window) was calculated during the first two-seconds of the MVIC and integrated (IEMG) for each trial. For the frequency analysis, the digitized sEMG data were band-pass filtered at 20-400 Hz using a fourth-order Butterworth filter with a zero lag, the first 500 ms of the sEMG data was removed, and then the next 1-s of the data was analyzed with a short-time Fourier transformation, and the median frequency (MF) of the spectrum was computed.

**Experimental Conditions:** Subjects performed MVICs in four randomized experimental conditions, with 10-min rest between conditions: (a) control, no taping (Figure 1a); (b) Knee Sleeve (Figure 1b); (c) KT (Figure 1c); and (d) sham (Figure 1d).

**Knee Sleeve application:** A knee sleeve (CORFLEX, Manchester, NH) was placed without any pressure on the knee joint.

**KT application:** The KT (Muscle Sports Tape, China; color: black; maximum rupture tension: 30 ± 3MPa; maximum strain tension: 120 ± 5 MPa) was applied with a Y-shape over the quadriceps according to Fu et al., by the same researcher. While subjects were seated with their hip flexed at 90º and the knee extended, tape was applied from a point 10 cm inferior to the anterior superior iliac spine bisected at

---

![Figure 1. Experimental Conditions: (a) control; (b) knee sleeve; (c) Kinesiology Tape (KT), and (d) sham.](image-url)
the junction between the quadriceps femoris tendon and the patella, and circled around the patella, ending at its inferior side. The first five cm of tape was not stretched and acted as the anchor. The portion between the anchor and superior patella was stretched to 120%. The remaining tape around the patella remained unstretched (Figure 1d).

Sham application: The KT was applied in the same pattern as KT condition, however, the tape was not stretched (Figure 1d).

Statistical Analyses
Normality and homogeneity of variance within the data were confirmed by the Shapiro-Wilk and Levene’s tests, respectively. Repeated measures ANOVAs were used to test differences between conditions for all dependent variables. Post-hoc comparisons were performed with the Bonferroni test. Cohen’s formula for effect size (d) was calculated, and the results were based on the following criteria: trivial (<0.2), small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0), and very large (>2.0) effects. An alpha value of 0.05 was used to determine statistical significance.

RESULTS
Test-retest reliability was calculated by intraclass correlation coefficient (ICC) and ranged between 0.82 and 0.97, and for all dependent variables. There were no statistical differences between conditions (p > 0.05) for passive tension, MVIC peak force, impulse, IEMG, or median frequency (Table 1). The effect sizes ranged between 0.10 and 0.55 (trivial-small) for all dependent variables.

DISCUSSION
The main findings of the present study confirmed the null hypotheses, that there was no significant difference between all experimental conditions, (including the control condition) for passive tension during the rest condition. KT is elastic cotton strips with an acrylic adhesive, and involves application of the tape while applying additional tension (~40%) to the tape and/or with the target muscle in a stretched position. In general, when the knee is flexed against an external resistance plus elastic adhesive (i.e. KT), the elastic material is stretched during the knee flexion phase, returning this energy during the knee extension phase. This potential accumulation of energy is purported to be transferred to the muscle, and added to the strength performance of the movement in the concentric phase. This additional effect on strength is known as passive tension of the material. To the best of authors’ knowledge, this was the first study to analyze passive tension during the rest condition with the knee flexed. This might help to evaluate any significant additional aid in performance that occurs from the KT. The effects of KT have been based on fascia

| Table 1. Descriptive data for all dependent variables across all conditions. Reported as Mean ± standard deviation [95% Confidence Interval]. |
|-----------------|----------------|----------------|----------------|
| Passive Tension (Kgf) | Control | Knee Sleeve | Kinesiology Tape | Sham |
| 10.25±4.0 | 8.26±3.2 | 8.84±3.3 | 8.41±2.5 |
| Peak Force (Kgf) | 485.40±76.0 | 469.08±78.6 | 508.01±92.0 | 497.31±102.0 |
| [447.51-523.28] | [429.98-508.18] | [462.06-554.12] | [446.60-548.14] |
| Impulse (Kgf.s) | 85.70±14.7 | 86.40±16.0 | 87.10±13.0 | 87.60±14.0 |
| [78.38-93.05] | [78.52-94.32] | [80.33-93.61] | [80.62-94.63] |
| IEMG (%MVIC.s) | 571.90±195.0 | 602.90±186.5 | 600.0±196.8 | 572.10±157.9 |
| [474.79-669.11] | [50.16-695.70] | [503.01-698.74] | [493.57-650.69] |
| Median Frequency (Hz) | 98.70±20.1 | 95.80±20.2 | 100.31±23.2 | 99.81±17.5 |
| [88.74-108.74] | [85.74-105.87] | [88.83-111.93] | [91.14-108.50] |

Kgf: Kilogram-force; IEMG: Integrated electromyography; MVIC: Maximal voluntary isometric contraction; Hz: Hertz.
traction as a main reason for an increase in muscular activation level.\textsuperscript{49} However, the results of the present study did not show differences between experimental conditions, and thus any additional passive tension from the KT or biological tissues (i.e. tendon, ligaments or joint capsule) does not appear to be relevant.

The second hypothesis was also confirmed, as KT did not affect muscle activation or force during MVICs. Several studies have analyzed the role of KT in force production of the knee extensors.\textsuperscript{4,5,9,17,18,28,31,34,36-38,51,52} Csapo and Alegre,\textsuperscript{49} in a meta-analysis, concluded that KT did not present significant effects on muscle strength, corroborating the results of this study. Additionally, Serra et al.\textsuperscript{36} did not observe significant differences in maximal knee extensor isometric force when KT was compared with Micropore (sham condition). In contrast, fewer studies\textsuperscript{4,17,28} have reported positive effects of KT on knee extensors isokinetic torque. Possibly, such results are related to baseline/training status of the subjects, lack of a control group, or type of contraction. Vithoulka et al.\textsuperscript{4} investigated quadriceps isokinetic muscular strength in three conditions (control, sham and KT) of healthy women. Their results showed that the application of KT increased eccentric isokinetic peak torque. Anandkumar et al.\textsuperscript{17} studied isokinetic torque of the quadriceps in individuals with knee osteoarthritis and observed that KT increased torque production. Finally, Yeung et al.\textsuperscript{18} observed that KT shortened the time required to generate maximal torque during isometric knee extension compared to a sham, and Wong et al.\textsuperscript{9} reported a significantly lower time to reach peak torque, in isokinetic contractions, in KT group when compared to a control condition.

Kase has suggested that the tape might affect muscle activity (motor unit recruitment) via the stimulatory effects arising from cutaneous mechanoreceptors.\textsuperscript{1} However, the results of the present study did not demonstrate differences between experimental conditions, indicating no change in muscular activation with or without KT exerting elastic tension on the skin. Lins et al.\textsuperscript{51} also observed no differences in the activation of vastus lateralis, rectus femoris and vastus medialis muscles, or knee flexion peak isokinetic torque at 60°/s. Additionally, neither Lins et al.,\textsuperscript{51} or Serrão et al.\textsuperscript{52} observed any significant differences in quadriceps muscle activation after KT application. Median frequency can represent motor unit firing rate and might be affected by sensory influence (inhibition or excitation) such as cutaneous mechanoreceptors.\textsuperscript{53,54} The lack of differences between experimental conditions in the present study for median frequency appears to reinforce the absence of inhibitory or excitatory effects of KT.

The present study has some limitations. Skinfold of the sEMG detection area was not controlled, which is considered to be a low-pass filter, and there may have been some inherent differences in the stiffness of the passive tissue between subjects. The present study analyzed a healthy, non-athletic population, and these results are not generalizable to other conditions, populations, or athletes.

Future research can be conducted using isometrics and similar methods at different knee angles, in dynamic testing conditions, or with different muscles. Additionally, this study only investigated acute effects of KT and studies that span longer wear time of kinesiology tape and longer term outcomes are warranted.

**CONCLUSIONS**

The results of the current study indicate that KT does not influence passive tension during static position at 90 degrees of knee flexion, nor does KT affect quadriceps activation or force production during a maximal voluntary isometric contraction.

**REFERENCES**


ABSTRACT

Background: Strengthening and activation of the gluteus maximus and gluteus medius while minimizing the contribution of the tensor fascia latae are important components in the treatment of many lower limb injuries. Previous researchers have evaluated a myriad of exercises that activate the gluteus maximus (GMax) and gluteus medius (GMed), however, limited research has been performed describing the role of the addition of elastic resistance to commonly used exercises.

Purpose: The primary purpose of this study was to determine the gluteal-to-tensor fascia latae muscle activation (GTA index) and compare electromyographic muscle activation of the GMax, GMed, and TFL while performing 13 commonly prescribed exercises designed to target the GMax and GMed. The secondary purpose of this study was to compare muscle activation of the GMax, GMed, and TFL while performing a subgroup of three matched exercises with and without elastic resistance.

Study Design: Repeated measures cohort study

Methods: A sample of 11 healthy, physically active male and females, free of low back pain and lower extremity injuries, were recruited for the study. Surface electromyography was used to quantify the normalized EMG activation of the gluteus maximus, gluteus medius, and tensor fascia latae while performing 13 exercises. Three of these exercises were performed with and without elastic resistance. The maximal voluntary isometric contraction was established for each muscle and order in which the exercises were performed was randomized to minimize the effect of fatigue.

Results: The relative activation of the gluteal muscles were compared to the tensor fascia latae and expressed as the GTA index. Clams with and without resistance, running man gluteus maximus exercise on the stability trainer, and bridge with resistance, generated the highest GTA index respectively. Significant differences in activation of the TFL occurred between clams with and without resistance.

Conclusions: The findings are consistent with those of previous investigators who reported that the clam exercise optimally activated the gluteal muscles while minimizing tensor fascia latae activation.

Levels of Evidence: Level 2b

Key Words: Elastic resistance, electromyography, gluteus maximus, gluteus medius
INTRODUCTION

A number of investigators have recently reported an association between abnormal hip mechanics and altered hip muscle performance and a variety of lower extremity and lower back conditions.1-9 The gluteus medius (GMed) is the major abductor of the hip and along with the gluteus maximus (GMax) performs most of the external rotation of the hip.10 The GMax is the major extensor of the hip and is also involved in hip abduction.10,11 The GMax inserts on the iliotibial tract, which is commonly referred to as the iliotibial band (ITB). Another muscle that inserts on the ITB is the tensor fascia latae (TFL). This muscle assists the GMed during hip abduction and assists in internal hip rotation. It is theorized that as a primary muscle responsible for a specific joint movement weakens, the synergistic muscle becomes the new primary muscle responsible for the movement.12-14 This theory has been supported by a number of studies reporting individuals with weak GMed and GMax muscles who exhibit signs of increased TFL activation and shortening.15 This increased TFL activation relative to GMed and GMax activation results in relative internal rotation of the hip and valgus positioning of the knee.1,13,15

The result of this change in mechanics can lead to numerous musculoskeletal problems including a variety of painful conditions of the lower back, hip, and knee. For instance, a weak GMax and GMed, have long been recognized to be associated with chronic lower back pain.16-18 Weak hip muscles and excessive internal rotation of the hip have also been strongly associated with patellofemoral pain syndrome (PFPS).1-3 Similarly, iliotibial band syndrome (ITBS) is a painful debilitating condition characterized by excessive internal hip rotation, gluteal weakness, and reduced extensibility of the ITB.14 Furthermore, atrophy of the GMax and the GMed relative to the TFL has been observed to accompany hip osteoarthritis.3,7,8 Finally, weakness of the hip abductors and external rotators resulting in valgus positioning of the knee has been associated with knee osteoarthritis.9,19

Extrapolating on these theorized and observed relationships between weak GMax, weak GMed, and compensatory activity of the TFL that accompany these conditions, clinicians have sought exercises that activate the GMax and GMed while limiting the recruitment of the TFL. Previous authors have studied the effects of exercises that activate the GMax and GMed.15,20-23 Bolgla et al.22 reported that weight bearing hip abduction exercises demonstrated greater activation of the GMed of the weight bearing leg compared with non-weight bearing leg. A recent review of commonly prescribed exercises to strengthen the GMax, and GMed based on electromyography (EMG) activation, described the degree to which each exercise activated the gluteal muscles. This article, however, failed to evaluate the activation of the TFL during these exercises.23 Other authors have reported increased activation of the gluteal muscles with the addition of elastic resistance, but again did not report TFL activation under these conditions.24 Finally, Cambridge et al.25 reported that placement of the elastic resistance on the knee versus the ankle and foot demonstrated lower activation of the GMax, GMed, and TFL during upright, semi-squat postures during side-stepping gait also called “sumo walks” and “monster walks.”

In one of the few studies that compared GMax, GMed, and TFL activation during various exercises, Selkowitz et al.,15 reported gluteal muscle activity based on fine wire EMG. They found that GMax and GMed activity was significantly greater than the TFL activity during unilateral and bilateral bridging, quadruped hip extension (knee flexed and hip moving into extension), the clam, sidestepping, and squatting. These authors also developed a gluteal-to-TFL muscle activation (GTA) index that combines the activation of the GMax and GMed muscles compared to the TFL for each of 11 exercises. Higher GTA index values indicate greater activation of the GMax and GMed relative to the TFL. The GTA index was highest for the clams, followed by the side-step, and unilateral bridge exercises. However, despite these results, the authors did not compare exercises with and without elastic resistance, a common modification used during treatment of patients to increase activation of the targeted muscles.

It is important to determine if the addition of elastic resistance to common hip exercises results in similar patterns of muscle activation among the GMax, GMed, and TFL. The primary purpose of this study was to determine the GTA index and compare muscle
activation of the GMax, GMed, and TFL while performing 13 commonly prescribed exercises designed to target the GMax and GMed. The secondary purpose of this study was to compare muscle activation of the GMax, GMed, and TFL while performing a subgroup of three matched exercises with and without elastic resistance.

METHODS

A convenience sample of 11 healthy, physically active males and females, free of low back pain and lower extremity injuries, were recruited for the study. Exclusionary criteria included no hip, back or lower extremity injuries or surgery within the past year. All data collection was performed in an outpatient physical therapy and chiropractic clinic in a repeated measures cohort study. Prior to participation in the study, all subjects were given an explanation of the study and provided written informed consent. This study was approved by an Institutional Review Board for trial in human subjects. Surface EMG was performed using a Noraxon Myosystem 1400A (Noraxon USA, Inc, Scottsdale, AZ) in order to quantify the activation of the GMax, GMed, and TFL. This was performed on the dominant leg while performing five repetitions of 13 exercises, three of which were also performed with elastic resistance (TheraBand®, Performance Health, Akron, OH). Participants wore comfortable, exercise clothing and all exercises were performed without shoes to prevent the influence of footwear differences.

The participants’ dominant leg was determined by asking which leg they would use to kick a soccer ball. The skin was prepped using an alcohol pad and surface electrodes (BIOPAC Systems, Inc. Camino Goleta, CA.) were placed on the GMax, GMed, and TFL muscles of the dominant side, based on the recommendations of Rainoldi et al.26 The GMax electrode was applied half the distance between the greater trochanter and the mid sacral vertebra (S3), at the level of the trochanter, on an oblique angle parallel to the muscle fiber direction. The GMed electrode was placed anterior to the GMax over the proximal 1/3 of the distance between the iliac crest and the greater trochanter, parallel to muscle fiber direction. Finally, the TFL electrode was applied approximately 2 cm below the anterior superior iliac spine, while the leg was extended, parallel to the muscle fiber direction. The reference electrode was placed over the right acromioclavicular joint.

Participants rode a stationary bike for five minutes with no resistance to warm-up prior to beginning testing. Following the warm-up, maximal voluntary isometric contraction (MVIC) was established for each muscle group. This was completed by using the manual muscle test position for the GMax, GMed, and TFL as described by Selkowitz, et al.15 For each muscle group, three repetitions, held for five seconds, were performed. The highest average peak value of the three repetitions, from the corresponding manual muscle test, was recorded as the MVIC of each muscle.

The sequence of exercises was randomized in order for each participant to minimize the influence of fatigue. The exercises selected are commonly prescribed for treating painful conditions of the back, hip and knee, and are consistent with the exercises studied by previous researchers.15,27 For the exercises that involved elastic resistance, the level of resistance was standardized so that the green colored TheraBand® Resistance Bands were used with the males and red colored bands were used with the females. The length of the resistance bands was determined when the subject had no slack or tension at the starting position of the exercise. The examined exercises included the following 13 exercises, with five repetitions of each exercise: [1] clams without resistance, [2] clams with resistance, [3] side-lying hip abduction without resistance, [4] prone hip extension without resistance, [5] quadruped hip extension without resistance, [6] quadruped hip extension with resistance, [7] bridge without resistance, [8] bridge with resistance, [9] standing hip abduction with resistance on the stance leg, [10] standing hip abduction with resistance on movement leg, [11] standing hip extension with resistance on the stance leg, [12] standing hip extension with resistance on the movement leg, and [13] running man gluteus maximus exercise on the stability trainer.

Visual onset and offset of the EMG signal amplitude was used to select the middle three of five repetitions of each of the 13 trials. The sampling frequency was 1000 Hz and the EMG signals were smoothed,
rectified, and analyzed using a root-mean-square algorithm of 100 ms to determine the peak activation for the GMax, GMed, and TFL. The average of the three repetitions was used for statistical analysis. The peak activation for each muscle was divided by the corresponding MVIC and expressed as a percent MVIC. This resulted in a percent activation for the GMax, GMed, and TFL during each of the exercises. The gluteal-to-TFL muscle activation (GTA) index was calculated as described by Selkowitz et. al. The GTA index employed the mean normalized EMG values to create relative activation ratios of both the GMax and GMed compared to the TFL. The relative activation ratio for each gluteal muscle was multiplied by that muscle’s mean normalized EMG value, summed, and then divided by two to provide the GTA index: $$\frac{([\text{GMed}/\text{TFL}] \times \text{GMed}) + ([\text{GMax}/\text{TFL}] \times \text{GMax})}{2}.$$

The GTA index value for each exercise was rank ordered from greatest (GMax and GMed activation relative to TFL activation) to smallest. These rankings are ordinal level and do not represent equal intervals in the GTA index scores relative to the exercises. A high score on the GTA index indicates there was a high normalized EMG amplitude for both of the gluteal muscles and they were both higher compared to the TFL.

A series of repeated measure of variance statistics (R-ANOVA) were calculated to determine if there were differences in the muscle activation of the GMax, GMed, and TFL while performing each of the 13 exercises. A significant ($p < .05$) main effect of muscle detected by the R-ANOVA, indicated post hoc comparisons using Tukey’s least significant differences to determine the specific differences between the means. Finally, comparisons were made between the activation of each muscle group with and without resistance during the three matched exercises using paired t-tests.

**RESULTS**

Five males and six females participated (mean age $27.18 \pm 7.33$ years and mean BMI $22.92 \pm 4.12$). Table 1 displays the GTA index and the relative rank of this index during the 13 exercises studied. The clams with resistance, clams without resistance, running man gluteus maximus exercise on the stability trainer without resistance, and bridge with resistance generated the highest GTA index respectively. The exercises that ranked lowest on the GTA index included quadruped hip extension without resistance and standing hip extension with resistance on the stance and movement leg.

Table 2 indicates that clams with ($F_{1,10}=30.77$, $p=0.00$) and without ($F_{1,10}=35.07$, $p=0.00$) resistance produced significantly higher activation of the GMax compared to GMed and TFL and higher activation of the GMed compared to TFL. Performing prone hip extension without resistance resulted in higher ($F_{1,10}=10.30$, $p=0.00$) GMax and GMed compared to TFL. GMed activation while side-lying hip abduction without resistance was higher ($F_{1,10}=8.60$, $p=0.02$) than either GMax or TFL activation. Similarly, activation of the GMed was greater ($F_{1,10}=5.70$, $p=0.004$) than the GMax during standing hip extension with resistance on the stance leg but similar to the activation of the TFL. The only other exercise that elicited differences in activation of the muscle groups was standing hip abduction with resistance on the stance leg.
leg with the activation of the GMax being lower than the GMed and the TFL ($F_{1,10} = 45.28, p = 0.00$). None of the remaining six exercises demonstrated significant differences in activating the GMax, GMed or TFL.

Comparisons in muscle activation of the GMax, GMed, and TFL while performing a subgroup of three matched exercises with and without elastic resistance indicated that the addition of resistance resulted in higher activation of only the TFL during the clams exercise ($T_{df=10} = 2.65, p = 0.02$). Activation of the GMax and Gmed were unaffected by the addition of resistance during the clam exercise. The addition of elastic resistance did not affect muscle activation during the quadruple hip extension or bridge.

**DISCUSSION**

Muscle weakness or imbalance of hip abductors and rotators, specifically the GMax, and GMed resulting in faulty lower extremity kinematics has been observed in a number of debilitating and painful conditions of the back, hip, and knee. There are several possible reasons for this including the inability to control the level of the pelvis and poor control of dynamic valgus at the knee. The results of the current study determined which exercises maximize the activation of the GMed and GMax while minimizing the activation of the TFL. During clams with and without resistance the activation of the GMax was highest followed by activation of the GMed and then the TFL. This difference in activation between the three muscles being studied was not exhibited during any of the other exercises studied. These findings are consistent with previous authors who reported that clam exercises activated the GMax and GMed while minimizing the activation of the TFL.

The ranking of the GTA index in Table 1 was similar to that of Selkowitz et al. Both studies ranked

---

**Table 2. Comparison of Mean Percent Activation While Engaging in Various Exercises With and Without Resistance.**

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Mean % Activation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gluteus Maximus</td>
</tr>
<tr>
<td>Clams with resistance † ‡ † ‡</td>
<td>42.0±19.31</td>
</tr>
<tr>
<td>Clams without resistance † ‡ † ‡</td>
<td>36.3±14.62</td>
</tr>
<tr>
<td>Quadruped Hip Extension without resistance</td>
<td>21.0±11.81</td>
</tr>
<tr>
<td>Bridge with resistance</td>
<td>38.3±13.43</td>
</tr>
<tr>
<td>Bridge without resistance</td>
<td>31.8±21.36</td>
</tr>
<tr>
<td>Standing Hip Abduction with resistance on movement leg</td>
<td>28.7±12.06</td>
</tr>
<tr>
<td>Standing Hip Abduction with resistance on the stance leg † ‡ † ‡</td>
<td>20.2±10.98</td>
</tr>
<tr>
<td>Standing Hip Extension with resistance on the stance leg † ‡ † ‡</td>
<td>16.4±8.71</td>
</tr>
<tr>
<td>Standing Hip Extension with resistance on the movement leg</td>
<td>18.7±8.31</td>
</tr>
<tr>
<td>Prone Hip Extension without resistance † ‡</td>
<td>30.9±11.50</td>
</tr>
<tr>
<td>Side-lying Hip Abduction without resistance † ‡ † ‡</td>
<td>34.4±14.37</td>
</tr>
<tr>
<td>Running Man on the Stability Trainer without resistance</td>
<td>50.9±21.38</td>
</tr>
</tbody>
</table>

† Indicates a significant difference ($p<0.05$) between Gluteus Maximus and Gluteus Medius for a specific exercise
‡ Indicates a significant difference ($p<0.05$) between Gluteus Maximus and Tensor Fascia Latae for a specific exercise
‡ ‡ Indicates a significant difference ($p<0.05$) between Gluteus Medius and Tensor Fascia Latae for a specific exercise
* Indicates significant difference ($p<0.05$) in specific muscle activation between exercises with and without resistance
the three common exercises using the GTA Index in the same order: the clams yielding the highest GTA index rank, followed by bridge, and then quadruped hip extension. In fact, both studies indicated that the GTA index, defined as relative activation of the GMax and GMed compared to the TFL, when performing clams, was approximately twice that of the GTA index when performing either the bridge or the quadruped hip extension. Only clams, bridge, and quadruped hip extension were exercises common to both the study conducted by Selowitz et al.15 and the current study. Both studies findings indicate that GMax and GMed activation were greater than TFL activation during the clam exercise. While only Selkowitz et al.15 reported significantly greater activation of the gluteal muscles over the TFL when performing the bridge and quadruped hip extension, the current study observed a similar, although not statistically significant pattern during the same exercises. This indicates a consistent higher activation of the GMax and GMed compared to the TFL during clams only. The lack of a significant difference between activation of the muscles during the bridge and quadruped hip extension compared to Selkowitz et al.15 may be attributable to the smaller sample size and a high degree variability of the measures within the current investigation. These consistent findings in activation patterns during these exercises provides evidence to the practitioner that the clams exercise may provide maximum activation of the gluteal muscles while minimizing activation of the TFL. Since this pattern of muscle activation is believed to be optimal for conditions related to hip muscle weakness, these findings in muscle activation patterns and ranking of the GTA index may warrant use of the clams exercise in patients with conditions involving poor hip biomechanics or hip muscle performance.

The results addressing the primary purpose of the study may be associated with a variety of factors. First, this study was conducted among healthy young adults without back or hip problems. It is possible that due to this, six of the thirteen exercises examined had similar activation of the GMax, GMed, and TFL. In addition, previous studies of individuals with back or hip problems indicated differences in the activation patterns of these muscles.3,4,18 This observation supports the theoretical relationships that as one muscle weakens, the synergistic muscle contributes as the new primary muscle.12-14 Finally, the results are consistent with the work of previous investigators15,20-25 who reported that the clams exercise may be a preferred exercise to activate the gluteal muscles while minimizing the relative activation of the TFL.

The results of the current study indicate that activation of the GMax, GMed, and TFL were predominately not changed as a result of adding resistance to the three exercises studied (clams, bridge, and quadruped hip extension). One possible explanation for this finding is that the level of resistance did not provide a sufficient stimulus to change the percentage activation of the muscles being studied in the young healthy population being studied. Assuming that the exercises elongated the TheraBand® Resistance Bands to twice their resting length (100 percent), the maximum amount of torque generated during the exercise would be 3.7 lbs and 4.6 lbs of force for the red band and green band respectively.28 It is possible that a heavier resistance would have generated a greater activation of these muscles compared to the activation observed when performing the exercises without resistance. Future studies may wish to examine activation patterns of the GMax, GMed, and the TFL with higher levels of resistance applied during the exercises.

Although enlightening, the results of this study need to be interpreted cautiously due to a number of limitations that future investigators may wish to address. First, the sample consisted of a small healthy group with a high degree of variability in the outcome measures. Future studies may wish to examine a larger more homogenous sample of individuals with a similar degree of chronic back pain. Second, muscle activation was based upon surface EMG technology that may have been affected by muscle activity beyond the targeted muscles being studied, e.g. “cross talk,” which is an inherent limitation of all surface EMG studies. Future studies replicating this design may wish to employ fine wire technology when measuring muscle EMG activity. Finally, the addition of elastic resistance in this study did not consistently result in a greater degree of muscle activation. This unexpected finding may be addressed by future
researchers applying a greater degree of elastic resistance during the exercises being examined.

CONCLUSIONS

The results of the current study indicate that certain exercises that target the gluteal muscles elicit a higher GTA index than others. The results of the current study provide support for certain exercises that target the GMed and GMax while minimizing the activation of the TFL. Specifically, the clams with and without elastic resistance as well as the running man gluteus maximus exercise on the stability trainer without resistance and the bridge with resistance yielded the highest GTA values. The use of elastic resistance during the clams increased the activation of the GMax and GMed to a greater degree than the increase in the TFL resulting in a higher GTA index and thus supports the use of resistance during this exercise as a way of minimizing TFL relative to Gmax/Gmed activation. These findings can direct clinicians when prescribing exercises to maximize activation of the gluteal muscles while limiting the tensor fascia latae involvement.

REFERENCES


ABSTRACT

Background: Generalized joint hypermobility is commonly measured using the Beighton and Horan Joint Mobility Index which provides a Beighton score of 0-9. Generally, scores of ≥4 are classified as hypermobile however joint hypermobility classification lacks consistency across the literature.

Purpose: The aim of the study was to compare the relative contribution of five joints to joint hypermobility scores in female and male rugby players, female netball players, female dancers and male and female age matched controls.

Study Design: Individual cohort study.

Methods: Joint hypermobility was assessed in 286 subjects using the Beighton and Horan Joint Mobility Index. Subjects were assigned a Beighton score of 0-9. These scores were then categorized using three different joint hypermobility classification systems and results were analyzed using a Pearson’s Chi Square (χ²) to report the relative contributions of each joint to hypermobility scores.

Results: Significant differences existed for group and gender analysis at the left and right 5th metacarpophalangeal joints, left and right thumb, left and right elbow and lumbar spine (p < 0.001). Lumbar flexion demonstrated significant χ² values and large effect sizes for all groups. This effect size was reduced to a moderate effect size when male against female analysis was performed and joint hypermobility was greater in females in comparison to males. The knee joint demonstrated the lowest hypermobility across all populations and ranged from 3% in male rugby players to 24% in female dancers. Seven hypermobile knees existed in males and 53 in females. Female dancers had the highest prevalence (93%) of hypermobile lumbar flexion and all female groups had a higher prevalence of hypermobile lumbar flexion than males. The removal of lumbar flexion from the total Beighton score had no effect on joint hypermobility prevalence in males in contrast to females where changes were demonstrated.

Conclusion: Joint hypermobility classification of female dancers should consider the high prevalence of hypermobility of lumbar flexion in interpretation. The consideration of separate classification systems for males and females, and between athletes of different sports and dancers may aid future understanding.

Levels of Evidence: 2b

Key words: Beighton score, female dancers, hypermobility, lumbar flexion.
INTRODUCTION

Joint hypermobility (JH) is excessive end of range joint motion in one or multiple joints. The original JH assessment was modified further by Beighton and Colleagues. The Beighton and Horan Joint Mobility Index (BHJMI) assesses joint range of motion (ROM) at the 5th metacarpophalangeal joints, thumbs, elbows, knees and lumbar spine which provides a Beighton score (BS) of 0 to 9. JH scores of ≥4 are classified as “hypermobile” however values of four, five and six have been utilized to classify JH.

JH is more prevalent in females than males with rates of 24% in male rugby players, 26.2% in students, 63% in female netballers and 66% in dance students. BHJMI interpretation may need to be sport or activity specific due to this varying prevalence. Within the JH literature there has been limited discussion regarding the relative joint contribution to JH and the potential implications this may have in terms of injury prevention and performance. The development of an enhanced understanding of joint contribution and reference values within varied populations may enhance management of individual athletes. JH may have performance benefits within dance. The exclusion of lumbar flexion from the criteria of JH diagnosis in dancers has been utilized due to the large lumbar flexion ROM required for dance performance however this has not been applied consistently in further studies. In netball, potential performance benefits may exist at the 5th metacarpophalangeal joint which has been reported to demonstrate the lowest JH of the BJHMI (15% of netballers had hyperextensibility of the 5th metacarpophalangeal joint). This may represent associated finger flexion conditioning and relate to increased neuromuscular tone which limits passive joint range. In netball, impaired movement control has been reported in individuals with general joint hypermobility. A relationship between performance benefits and JH has not been previously reported in rugby.

In dance, JH is associated with increased injury risk with both low BS (0-2) and high BS (5-9) dancers, who were 1.43 and 1.22 times more likely, respectively, to suffer injury than dancers in the medium BS group (3-4). JH has been associated with an increased risk of injury in netball, with 21% of netballers with a BS of 0-2 having sustained previous injury compared to 37% (BS 3-4) and 43% (BS 5-9). In rugby players with a BS 4-6, injury incidence (116.7 injuries/1000 hours) was significantly higher than those with a BS of 0-3 (43.6 injuries/1000 hours). There has been no focus on joint contribution in previous studies and due to the contact nature of rugby, JH may be a risk factor for injury and there is a potential need for enhanced understanding of JH to reduce the potential risk of injuries such as dislocation and subluxation. Different JH classification systems have been utilized and therefore to aid interpretation of joint contribution the current study used three JH classification systems.

Recurrent musculoskeletal pain can be a manifestation of JH and may predispose an athlete to trauma. Asymmetrical joint surface loading contributes to joint surface wear and the joint may progress from being “loose” to “loose and painful”. Pain may originate from joint stretch receptors and swelling of the joint lining and can often be the first sign that JH problems may exist which therefore may act as a warning sign to clinicians to monitor the individual carefully to potentially reduce injury risk.

The aim of the study was to compare the relative contribution of five joints to joint hypermobility scores in female and male rugby players, female netball players, female dancers and male and female age matched controls.

METHODS

Participants

Two hundred and eighty-six subjects volunteered to participate in this study including 65 female rugby players (FR), 38 male rugby players (MR), 61 netball players (NP), 42 female dancers (FD), 40 aged matched male subjects (MS) and 40 aged matched female subjects (FS). Recruitment was aimed at attaining age-matched groups and the sport and dance groups were standardized for weekly participation levels. Female and male controls were recruited by asking for volunteers via a poster campaign within the university. All subjects were 18 years of age or older and were excluded from the study if they had suffered an injury in the previous
30 days which prevented training, match or dance class participation. Subjects completed a medical screening questionnaire prior to participating in the study and additional exclusion criteria included heart disease and pregnancy. Participation was voluntary and subjects were provided with information sheets and completed informed consent forms prior to participation. The University Research Ethics Committee provided ethical approval (SPA-REC-2015-185) in accordance with the Helsinki declaration.

**Procedures**

All testing was conducted indoors under the supervision of the same researcher and prior to testing the subjects’ height (cm) was measured using a stadiometer (Leicester Height Measure, Child Growth Foundation) and body mass (kg) were recorded using digital scales (Salter 9028, Kent, UK). The subjects date of birth and ethnicity was recorded and participation in other sports and dance was determined prior to testing to ensure that subjects did not cross participate in the observed genres.

**JH screening**

Testing was conducted prior to training or dance classes to prevent any potential effects of exercise on JH and subjects did not participate in exercise for at least 12 hours prior to testing due to the potential effects of warm up on joint ROM. The BS was used to measure JH and has an Intraclass Correlation Coefficient (ICC) of 0.91 and a kappa 0.74. The same clinician performed the assessment, specifically a Chartered Physiotherapist with 15 years' experience in BS classification by measuring ROM of the 5th metacarpophalangeal joints (1 point each joint), thumbs (1 point each joint), elbows (1 point each joint), knees (1 point each joint) and lumbar spine (1 point) which provided a maximum score of 9. A goniometer (Vivomed, UK) was used to measure all joints except the lumbar spine for which JH was classified as yes/no based on the participants ability to put the palms of their hands flat on the floor. All tests were performed as described by Juul-Kristensen and colleagues. The first classification system (BE) as used by Beighton and colleagues classifies JH as a score of ≥ 4. The second classification system (B) as used by Boyle and colleagues provides three sub-categories: 0-2 = (not hypermobile, NH); 3-4 = (moderately hypermobile, MH); 5-9 = (distinctly hypermobile, DH) and has a percentage agreement (81%) and spearman rho for intra-rater reliability (0.81) and interrater reliability (89% and 0.75) for these sub-category scores. The third classification system (SB) as described by Stewart and Burden provided three sub-categories: 0-3 = (tight, NH); 4-6 = (hypermobile, (H)) and 7-9 = (distinctly hypermobile, DH). The term ‘tight’ was used to define individuals who had non-lax ligaments however the current study prefers to utilise the term NH for this category so as to be consistent in terminology. Three classification systems were used to allow a comprehensive comparison as the BE does allow further sub-categorisation of JH.

Intra-rater reliability was assessed by the Chartered Physiotherapist by measuring JH using the BS of 20 subjects not involved in the study on 2 separate occasions 24 hours apart. The Chartered Physiotherapist was blinded to previous results to allow determination of ICC's ($\kappa$). Subjects were instructed not to participate in sport, dance activity or warm up during this 24 hour period. This timescale was selected to reduce the potential for ROM adaptations. Intra-rater reliability for the total BS had an ICC of 0.992 (95% Confidence Intervals 0.979-0.997) indicating excellent reliability.

Statistical analysis

Absolute scores and percentages were calculated for JH and for the contribution of each joint to JH. Hypermobility was defined as absent (0) or present (1) at each joint and a Pearsons Chi Square ($\chi^2$) was used to analyse observed and expected frequencies at each joint across the six groups and contingency tables created. Analysis included all groups, male against females and female dancers against all other subgroups. Observed and expected frequencies were calculated for each group and standardised residuals were utilised providing Z scores which were classified as $+/− 1.96$ to $+/− 2.57$ ($P < 0.05$), $+/− 2.58$ to $+/− 3.28$ ($P < 0.01$) and $≥ +/− 3.29$ ($P < 0.001$). Cramers V was used to calculate effect size with effects sizes graded as 0.1(Small), 0.3(Medium), 0.5(Large). Significance was accepted at $P < 0.05$ and all statistical analysis was performed using SPSS version 23 software (IBM Inc.)
RESULTS
The demographics of subjects were as follows: 65 FR, (65 white Caucasian, age: 20.89 ± 1.91 years, height: 164.94 ± 9.13 cm, mass: 71.76 ± 17.67 kg), 38 MR, (36 white Caucasian, 2 black Caribbean, age: 21.03 ± 2.1 years, height: 181.79 ± 6.29 cm, mass: 87.60 kg ± 12.78 kg), 61 NP (61 white Caucasian, age: 20.18 ± 1.2 years, height: 168.80 ± 7.71 cm, mass: 65.34 ± 10.57 kg), 42 FD (41 white Caucasian, 1 Hispanic, age: 20.01 ± 1.03 years, height: 162.74 ± 7.20 cm, mass: 58.77 ± 5.29 kg), 40 MS (39 white Caucasian, 1 Asian age: 20.15 ± 1.43 years, height: 176.38 ± 7.64 cm, mass: 77.98 ± 9.81 kg), and 40 FS (39 white Caucasian, 1 black African, age: 20.23 ± 1.11 years, height: 164.5 ± 7.92 cm, mass: 63.78 ± 9.92 kg).

Table 1 summarizes the frequency of JH by joint location (percentage of group value) of the six participant groups.

Table 2 summarizes BS as a percentage of group value within each category of classification when the flexion component of the BS is included and then removed (value in brackets) across the six participant groups.

<table>
<thead>
<tr>
<th>Joint</th>
<th>FR (%)</th>
<th>MR (%)</th>
<th>NP (%)</th>
<th>FD (%)</th>
<th>MS (%)</th>
<th>FS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>49</td>
<td>26</td>
<td>62</td>
<td>86</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>RF</td>
<td>38</td>
<td>26</td>
<td>49</td>
<td>83</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>LT</td>
<td>28</td>
<td>24</td>
<td>41</td>
<td>65</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>RT</td>
<td>32</td>
<td>18</td>
<td>37</td>
<td>56</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>LE</td>
<td>31</td>
<td>11</td>
<td>18</td>
<td>40</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>RE</td>
<td>20</td>
<td>11</td>
<td>26</td>
<td>57</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>LKL</td>
<td>43</td>
<td>8</td>
<td>41</td>
<td>93</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>LK</td>
<td>12</td>
<td>3</td>
<td>7</td>
<td>21</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>RK</td>
<td>11</td>
<td>3</td>
<td>7</td>
<td>24</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

FR; Female Rugby Players, MR; Male Rugby Players, NP; Netball Players, FD; Female Dancers, MS; Male Subjects, FS; Female Subjects; LF; Left 5th metacarpophalangeal joint, RF; Right 5th metacarpophalangeal joint, LT; Left Thumb, RT; Right Thumb, LE; Left Elbow, RE; Right Elbow, LKL; Lumbar Flexion, LK; Left Knee, RK; Right Knee

<table>
<thead>
<tr>
<th>CS</th>
<th>FR (%)</th>
<th>MR (%)</th>
<th>NP (%)</th>
<th>FD (%)</th>
<th>MS (%)</th>
<th>FS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be (0-3) NH</td>
<td>72 (75)</td>
<td>92 (92)</td>
<td>67 (69)</td>
<td>12 (17)</td>
<td>93 (95)</td>
<td>68 (68)</td>
</tr>
<tr>
<td>Be (24) H</td>
<td>28 (25)</td>
<td>8 (8)</td>
<td>33 (31)</td>
<td>88 (83)</td>
<td>8 (5)</td>
<td>33 (33)</td>
</tr>
<tr>
<td>B (0-2) NH</td>
<td>57 (65)</td>
<td>87 (87)</td>
<td>48 (57)</td>
<td>5 (13)</td>
<td>85 (85)</td>
<td>48 (55)</td>
</tr>
<tr>
<td>B (3-4) MH</td>
<td>22 (23)</td>
<td>11 (11)</td>
<td>28 (28)</td>
<td>14 (48)</td>
<td>13 (13)</td>
<td>28 (28)</td>
</tr>
<tr>
<td>B (5-9) DH</td>
<td>22 (15)</td>
<td>3 (3)</td>
<td>25 (15)</td>
<td>81 (40)</td>
<td>3 (3)</td>
<td>25 (18)</td>
</tr>
<tr>
<td>SB (0-3) NH</td>
<td>72 (75)</td>
<td>92 (92)</td>
<td>67 (69)</td>
<td>12 (17)</td>
<td>93 (95)</td>
<td>68 (68)</td>
</tr>
<tr>
<td>SB (4-6) H</td>
<td>20 (23)</td>
<td>5 (5)</td>
<td>26 (31)</td>
<td>67 (79)</td>
<td>5 (5)</td>
<td>30 (33)</td>
</tr>
<tr>
<td>SB (7-9) DH</td>
<td>8 (2)</td>
<td>3 (3)</td>
<td>7 (7)</td>
<td>21 (5)</td>
<td>3 (3)</td>
<td>3 (6)</td>
</tr>
</tbody>
</table>

CS; Classification System, FR; Female Rugby Players, MR; Male Rugby Players, NP; Netball Players, FD; Female Dancers, MS; Male Subjects, NH; Not Hypermobile, H; Hypermobile; MH; Moderately Hypermobile; DH; Distinctly Hypermobile; BE; Beighton; B; Boyle, SB; Stewart and Burden
Figure 1 displays the percentage contribution of positive joint hypermobility at each joint for all participants.

Table 3 reports Chi square, Z and Cramer V probability scores for JH across the six groups. Group analysis of the joints revealed significant differences (p < 0.001) at the left and right 5th metacarpophalangeal joints, left and right thumb joints for all groups with female dancers and male controls Z scores significant at these joints. At the left and right elbow and lumbar joints significant differences existed for all groups (p < 0.001) with female dancers, male rugby and male control Z scores significant at these joints. At the right knee significant differences existed for all groups (p = 0.020) and female dancers Z scores were significant. Large effect sizes (0.541) existed for lumbar flexion.

Table 4 reports Chi square, Z and Cramer V probability scores for JH as a comparison between male and female subjects. Male subjects demonstrated significant Z scores for left and right 5th metacarpophalangeal joints, left and right thumb, left elbow and lumbar flexion. A medium effect size (0.331) existed for lumbar flexion. Comparison of male and female subjects revealed significant findings (p < 0.001) for left and right 5th metacarpophalangeal joints, left and right thumb, left and right elbow and lumbar flexion and at the (p < 0.05) level for left and right knee. Cramers Values were: left metacarpophalangeal joint 0.293; right metacarpophalangeal joint 0.234; left thumb 0.210; right thumb 0.254; left elbow 0.207; right elbow 0.225; lumbar flexion 0.331; left knee 0.118; right knee 0.122.

Table 5 reports Chi square and Z scores for JH as a comparison between female dancers and each
subgroup. Significant differences existed between female dancers and all groups for left and right metacarpophalangeal joints (p < 0.001, left and right elbow (p < 0.001 to p = 0.044) and lumbar flexion (p < 0.001).

Table 6 reports Cramer V probability scores for JH as a comparison between female dancers and each subgroup. Significant differences existed between female dancers and all groups for left (p < 0.001 to p = 0.009) and right metacarpophalangeal joints (p < 0.001), left (p < 0.001 to p = 0.044) and right elbow (p < 0.001 to p = 0.023) and lumbar flexion (p < 0.001).

**DISCUSSION**

The aim of this study was to compare the relative joint contributions to JH scores across gender, sports and dance participation. The knee joint demonstrated the lowest JH across all populations and ranged from 3% (male rugby) to 24% (female dancers). Within male subgroups, 9% of knees were hypermobile in comparison to 25% in females in agreement with the female dancer group.
with previous findings of increased knee joint laxity in females. As left and right knee are the only measurements of hypermobility performed in the lower limb there may be a need to measure other joints such as the ankle or toes to provide a more specific measure of body joint hypermobility. This may have particular importance in dance which requires movements such as “en pointe” which increase the stress on these joints. Within netball players the high prevalence of 5th metacarpophalangeal JH in comparison to female rugby players and female controls may represent a sporting adaptation. This is in contrast to previous research in elite netballers that found this to be the least hypermobile joint and may reflect the different levels of netballer.

Lumbar flexion demonstrated significant $\chi^2$ values and large effect sizes for all groups however this effect size was reduced to a medium effect size when male against female analysis was performed. This highlights the need for the careful consideration of inclusion of this measurement in determining JH. Particular caution is required with female dancers with this study demonstrating a lumbar flexion JH rate of 93% for this cohort. Lumbar forward flexion is acquired through dance training and lumbar

### Table 5. Chi square and Z scores for joint hypermobility: a comparison between female dancers and other groups.

<table>
<thead>
<tr>
<th>Joint</th>
<th>FD &amp; FR</th>
<th>FD &amp; MR</th>
<th>FD &amp; NP</th>
<th>FD &amp; MS</th>
<th>FD &amp; FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>$X^2$ 15.757 (DF 1)</td>
<td>$X^2$ 28.803 (DF 1)</td>
<td>$X^2$ 6.744 (DF 1)</td>
<td>$X^2$ 33.063 (DF 1)</td>
<td>$X^2$ 24.125 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.009†</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
</tr>
<tr>
<td>FR</td>
<td>$X^2$ 26.555 (DF 1)</td>
<td>$X^2$ 12.462 (DF 1)</td>
<td>$X^2$ 35.539 (DF 1)</td>
<td>$X^2$ 30.491 (DF 1)</td>
<td>$X^2$ 30.491 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
</tr>
<tr>
<td>LT</td>
<td>$X^2$ 18.477 (DF 1)</td>
<td>$X^2$ 1.173 (DF 1)</td>
<td>$X^2$ 1.27 (DF 1)</td>
<td>$X^2$ 0.279 (DF 1)</td>
<td>$X^2$ 0.279 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
</tr>
<tr>
<td>RT</td>
<td>$X^2$ 8.745 (DF 1)</td>
<td>$X^2$ 1.48 (DF 1)</td>
<td>$X^2$ 17.876 (DF 1)</td>
<td>$X^2$ 0.827 (DF 1)</td>
<td>$X^2$ 0.827 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p = 0.067</td>
<td>p = 0.003*</td>
<td>p = 0.001*</td>
<td>p = 0.363</td>
<td>p = 0.363</td>
</tr>
<tr>
<td>LE</td>
<td>$X^2$ 19.056 (DF 1)</td>
<td>$X^2$ 15.361 (DF 1)</td>
<td>$X^2$ 15.684 (DF 1)</td>
<td>$X^2$ 4.040 (DF 1)</td>
<td>$X^2$ 4.040 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p = 0.007†</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p = 0.044†</td>
<td>p = 0.044†</td>
</tr>
<tr>
<td>RE</td>
<td>$X^2$ 17.459 (DF 1)</td>
<td>$X^2$ 8.607 (DF 1)</td>
<td>$X^2$ 21.134 (DF 1)</td>
<td>$X^2$ 5.135 (DF 1)</td>
<td>$X^2$ 5.135 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p = 0.023†</td>
<td>p = 0.023†</td>
</tr>
<tr>
<td>LFL</td>
<td>$X^2$ 57.749 (DF 1)</td>
<td>$X^2$ 28.449 (DF 1)</td>
<td>$X^2$ 50.154 (DF 1)</td>
<td>$X^2$ 44.453 (DF 1)</td>
<td>$X^2$ 44.453 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
<td>p &lt; 0.001*</td>
</tr>
<tr>
<td>LK</td>
<td>$X^2$ 6.445 (DF 1)</td>
<td>$X^2$ 4.988 (DF 1)</td>
<td>$X^2$ 3.182 (DF 1)</td>
<td>$X^2$ 2.021 (DF 1)</td>
<td>$X^2$ 2.021 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p = 0.208</td>
<td>p = 0.266†</td>
<td>p = 0.074</td>
<td>p = 0.654</td>
<td>p = 0.654</td>
</tr>
<tr>
<td>RK</td>
<td>$X^2$ 5.745 (DF 1)</td>
<td>$X^2$ 6.304 (DF 1)</td>
<td>$X^2$ 5.802 (DF 1)</td>
<td>$X^2$ 2.760 (DF 1)</td>
<td>$X^2$ 2.760 (DF 1)</td>
</tr>
<tr>
<td></td>
<td>p = 0.072</td>
<td>p = 0.016†</td>
<td>p = 0.097</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
</tr>
</tbody>
</table>
|       | p < 0.05 for Z score, †=Significant p-value < 0.001, ‡=Significant p-value, ††= p < 0.01 for Z score, **= p < 0.001 for Z score.
flexion JH rates of 91.5% in 47 dancers and a rate of 6.4% have been reported in age and gender matched controls. In the current study, 88% (n = 37) female dancers were hypermobile, in contrast previous literature reported JH rates of 66% (n = 24, BS ≥ 4 ) in professional female dancers and only 4.3% (n = 2, BS ≥ 4) in professional ballet dancers however in this study 36% of participants were male. After female dancers the highest prevalence of lumbar flexion JH was female rugby players 43% (n = 28), netball players 41% (n = 25), female controls 20% (n = 8), male controls 15% (n = 6) and male rugby players 8% (n = 3) highlighting a gender difference. At the upper limb joints and on lumbar flexion male subgroups demonstrated reduced hypermobility levels to expected X2 values.

In relation to the number of subjects with JH the removal of lumbar flexion from the three hypermobility classifications resulted in no change in “not hypermobile” (NH) scores across the three classifications in male rugby and an increase of 5% (n = 2) in male controls (BE and SB). In netball players, the B classification (0-2) increased by 9.8% (n = 6) in comparison to the BS and BE classification increase of 1.6% (n = 1) while female rugby remained similar at 3% (n = 2) (BE and SB) and 8% (n = 5) (B). Female dancers demonstrated large changes in the B classification ‘moderately hypermobile” (MH) (3-4) with an increase of 33.3% (n = 14) in contrast to a decrease of -4.8% (n = -2) and increase of 11.9% (n = 5) respectively in the BE (≥4) and SB “hypermobile” (4-6) classifications. This highlights classification system variation and influence of lumbar flexion inclusion. The other populations demonstrated smaller changes ranging from an increase of 4.9% (n = 3) in netball players SB (4-6) “hypermobile” to no change in male subgroups across all classifications. Within the categorisation of B “distinctly hypermobile” (DH) (5-9) and SB DH (7-9) there were no changes in male subgroups. In females changes occurred in all groups with female dancers demonstrating noticeable differences across the classifications with a decrease of -40.1% (n = -17) in the B classification and a decrease of -16.7% (n = -7) in SB classification. The removal of lumbar flexion from total BS had no

<table>
<thead>
<tr>
<th>Joint</th>
<th>FD &amp; FR</th>
<th>FD &amp; MR</th>
<th>FD &amp; NP</th>
<th>FD &amp; MS</th>
<th>FD &amp; FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>CV 0.384</td>
<td>CV 0.660</td>
<td>CV 0.256</td>
<td>CV 0.635</td>
<td>CV 0.542</td>
</tr>
<tr>
<td></td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.009†</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
</tr>
<tr>
<td>RF</td>
<td>CV 0.441</td>
<td>CV 0.574</td>
<td>CV 0.348</td>
<td>CV 0.658</td>
<td>CV 0.610</td>
</tr>
<tr>
<td></td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
</tr>
<tr>
<td>LT</td>
<td>CV 0.362</td>
<td>CV 0.408</td>
<td>CV 0.229</td>
<td>CV 0.475</td>
<td>CV 0.120</td>
</tr>
<tr>
<td></td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.020†</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.279</td>
</tr>
<tr>
<td>RT</td>
<td>CV 0.177</td>
<td>CV 0.331</td>
<td>CV 0.106</td>
<td>CV 0.467</td>
<td>CV 0.100</td>
</tr>
<tr>
<td></td>
<td>CV p = 0.067</td>
<td>CV p &lt; 0.003†</td>
<td>CV p &lt; 0.284</td>
<td>CV p &lt; 0.001*</td>
<td>CV p = 0.363</td>
</tr>
<tr>
<td>LE</td>
<td>CV 0.262</td>
<td>CV 0.488</td>
<td>CV 0.386</td>
<td>CV 0.437</td>
<td>CV 0.222</td>
</tr>
<tr>
<td></td>
<td>CV p &lt; 0.0007†</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p = 0.044†</td>
</tr>
<tr>
<td>RE</td>
<td>CV 0.359</td>
<td>CV 0.467</td>
<td>CV 0.289</td>
<td>CV 0.508</td>
<td>CV 0.250</td>
</tr>
<tr>
<td></td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p = 0.023†</td>
</tr>
<tr>
<td>LFL</td>
<td>CV 0.502</td>
<td>CV 0.85</td>
<td>CV 0.526</td>
<td>CV 0.782</td>
<td>CV 0.736</td>
</tr>
<tr>
<td></td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
<td>CV p &lt; 0.001*</td>
</tr>
<tr>
<td>LK</td>
<td>CV 0.122</td>
<td>CV 0.284</td>
<td>CV 0.220</td>
<td>CV 0.197</td>
<td>CV 0.050</td>
</tr>
<tr>
<td></td>
<td>CV p = 0.208</td>
<td>CV p = 0.11</td>
<td>CV p = 0.264†</td>
<td>CV p = 0.074</td>
<td>CV p = 0.654</td>
</tr>
<tr>
<td>RK</td>
<td>CV 0.174</td>
<td>CV 0.307</td>
<td>CV 0.247</td>
<td>CV 0.266</td>
<td>CV 0.183</td>
</tr>
<tr>
<td></td>
<td>CV p = 0.208</td>
<td>CV p = 0.066†</td>
<td>CV p = 0.012†</td>
<td>CV p = 0.016†</td>
<td>CV p = 0.097</td>
</tr>
</tbody>
</table>


*= p < 0.001, †=Significant p- value
effect on JH prevalence in male subgroups in contrast to females and therefore there may be a need to consider this in JH interpretation. Other female subgroups demonstrated smaller reductions within the two classifications.

Within dance the generally untrained joints of the 5th metacarpophalangeal, thumbs and elbows may provide an indication of general JH and are unlikely to have been exposed to the potential performance adaptation associated with lumbar flexion. Female dancers had the lowest percentage JH contribution (73%) from these three joints which may demonstrate a performance related adaptation that results in lumbar flexion and the knee joint contributing more. In both male subgroups lumbar flexion was restricted in comparison to females which may be related to poor hamstring flexibility which can influence this measurement. The finger tips to floor test which involves the same movement has been shown to be a reliable measure of hamstring flexibility. This involves contribution of the hip, wrist, fingers, elbows and shoulders and therefore is not an isolated joint movement like the other measurements. Such functional movements may require different interpretation within the BS. There may be a need for interpretation of the lumbar flexion movement to be combined with performance of a Schöbers or Schöbers modified test to determine the contribution of the lumbar spine. The Schöbers test involves palpating and marking the lumbosacral junction and then marking another point 10cm superiorly and asking participants to flex as far forwards as possible while ensuring the knees remain fully extended and the distance between the two points is measured. The modified version uses the same movement and marks and requires the addition of a mark 5cm below the lumbosacral junction and the distance between this mark and the mark made 10cm above lumbosacral junction is measured with participant in a flexed position. Test retest reliability of these two methods has been reported as \( r = 0.87 \) indicating excellent reliability. A straight leg raise test could be used to determine hamstring ROM contribution more effectively.

The comparison between female dancers and other subgroups revealed significant findings between female dancers and female rugby players and medium to large effects sizes existed for all joints except the right thumb and both knees. Female dancers and netball players analysis was significant at all joints except the right thumb and medium effect sizes existed at the right 5th metacarpophalangeal and left elbow joints. Female dancers and female control analysis revealed significant findings at all joints except at both thumbs and knees and large effect sizes at both 5th metacarpophalangeal joints and the lumbar spine. Female dancers and male rugby players analysis revealed significant findings and medium to large effect sizes at all joint except the left knee. Analysis of female dancers and male controls revealed significant differences at all joints except the left knee and medium to large effect sizes existed at all joints except the knee. At the left and right knee differences between groups and gender were less prominent with only female dancers demonstrating significant findings. At all joint locations, JH was higher in females than males supporting the greater prevalence of female JH and therefore females may need to be categorised differently. Although the purpose of this study was not to compare total JH scores it must be acknowledged that with all three classification systems the prevalence of JH was greatest in female dancers even with lumbar flexion removed and the values were greater than those previously reported.

JH classification in rugby union, netball and dance via three different classifications systems suggests that the consideration of gender, sport and dance participation is important in determining normal vales and there is a need to consider age, gender and ethnicity. The current findings have clinical importance as decisions regarding injury prevention, training load and sport selection based on the BS should consider carefully joint contribution to JH scores. Gender and predominant activity of the individual is important and should be compared with expected values within the domain and the potential contribution to injury risk or performance variation should be considered. Currently the interpretation of total JH score may not be the best practice due to gender and sport variations in lumbar flexion JH, knee JH and the contribution of upper limb to total JH score. The findings may demonstrate a continuum of hypermobility which may demonstrate
either a performance adaptation or selection bias highlighted by the differences between male and female subgroups with female dancers and netball players demonstrating greater hypermobility than female rugby players. The initial implementation of the BS was as an epidemiological tool and not as a sport or dance specific tool and therefore the development of sport or dance specific grading scales seems a logical progression.

The results of the study are limited to the populations investigated and the classification systems used do not report specific joint ROM. Further studies should consider male dancers, report joint ROM and utilize a larger sample size. It appears that further investigation of increased female JH at the knee joint is required as well as additional reports on the prevalence of 5th finger metacarpophalangeal hypermobility in netball players. Long term studies that potentially measure changes in JH with relation to participation in varied sports or dance performance may allow determination of potential long-term performance adaptations. Future research assessing JH of female dancer may benefit from providing two scores which include and exclude lumbar flexion as female dancers may have a different normal range for this measurement.

CONCLUSION

Females and males are subject to differences in the relative contribution to JH and the functional nature of lumbar flexion may require different interpretation within the BS. Within female dancers, a positive lumbar flexion JH score may be a sign of performance adaptation rather than a measure of JH and therefore its inclusion within JH grading within this group requires careful consideration.

REFERENCES


ABSTRACT

Background: Scapular substitution is an alteration of scapulohumeral kinematics that may occur when patients have shoulder pain or dysfunction. These abnormal scapular kinematic patterns have been recognized in patients with rotator cuff tears. It remains unknown if 1) normal scapular kinematics can be restored with rehabilitation after rotator cuff repair surgery and 2) abnormal scapular kinematics are associated with inferior patient-determined outcome scores, range of motion, or strength.

Purpose: The purpose of this study was to determine 1) if scapular substitution can be decreased or improved with rehabilitation after rotator cuff repair surgery and 2) if the presence or amount of scapular substitution was correlated with patient-determined outcome scores, range of motion, or strength after rotator cuff repair surgery.

Study Design: Retrospective review of prospectively collected data (LOE IV)

Methods: Forty-eight patients who underwent post-operative rehabilitation after an arthroscopic rotator cuff repair were reviewed for this study. The outcomes measures of interest included: patient-determined outcome scores (WORC, Simple Shoulder Test, the ASES Score, the Shoulder Activity Score, and the SANE rating), identification and quantification of scapular substitution, active range of motion, and strength. Outcomes were prospectively collected up to 12 months after surgery and assessed retrospectively.

Results: As patients progress through their first year of rehabilitation from a rotator cuff repair, the amount of scapular substitution decreases but remains statistically significantly greater than the contralateral, asymptomatic side. At all post-operative time points, patients with scapular substitution, (determined subjectively by a physical therapist), had 1) inferior WORC, ASES, SANE, and SST scores, 2) inferior flexion, abduction, and external rotation range of motion, and 3) inferior scaption strength compared to those patients without subjective scapular substitution.

Conclusions: Rehabilitation decreases but does not normalize the amount of scapular substitution up to one year after rotator cuff repair. Subjective identification of scapular substitution is associated with inferior patient-determined outcome scores, range of motion, and strength.

Level of Evidence: 4 – Prognosis study

Keywords: Patient outcomes; rotator cuff repair; scapular kinematics; scapular substitution

CORRESPONDING AUTHOR
Keith M. Baumgarten, MD
810 E 23rd Street
Sioux Falls, SD 57117
E-mail: kbaumga@yahoo.com
BACKGROUND
Scapular substitution is an alteration of scapulo-humeral kinematics that may occur when patients have shoulder pain or dysfunction. Blevins et al have described the clinical observation of scapular substitution as the “shrug sign.”1 When normal 3-dimensional scapular kinematics are examined during shoulder elevation, the scapula rotates laterally, tilts posteriorly, and protracts/retracts depending on the plane of elevation.2 When scapular kinematics are examined in 2-dimensions (which does not require expensive or complex laboratory equipment), the scapula translates both medially and vertically with forward elevation and elevation in the scapular plane (scaption) movements of the shoulder.3,4 In patients with shoulder pain and dysfunction, the vertical and medial translation of the scapula becomes further accentuated and has been termed scapular substitution since the scapulothoracic joint appears to substitute for loss of motion at the gleno-humeral joint.4,5 This increase in scapular elevation has been associated with increased activity of the trapezius and decreased serratus anterior activity during arm elevation.6 Although abnormal scapular kinematic patterns have been recognized in asymptomatic, well-functioning individuals,7-10 they have also been demonstrated in postoperative patients,2 patients with rotator cuff impingement,6,11-15 rotator cuff tears,16-19 glenohumeral instability,15 osteoarthritis,2 adhesive capsulitis,2,20 and patients after reverse total shoulder arthroplasty.20

One observational study revealed that scapular kinematic alterations can improve with verbal instruction and practice.5 However, longitudinal studies that examine if scapular kinematics can be improved with rehabilitation after surgery are rare.21 In addition, studies do not exist that examine the correlation of scapular kinematics with patient-determined outcome scores, range of motion, or strength.

The purpose of this study was to determine 1) if scapular substitution can be decreased or improved with rehabilitation after rotator cuff repair surgery and 2) if the presence or amount of scapular substitution was correlated with patient-determined outcome scores, range of motion, or strength after rotator cuff repair surgery. The hypothesis of this study was that rehabilitation after rotator cuff repair surgery would decrease the amount of scapular substitution over time. In addition, patients with increased scapular substitution would have inferior outcomes in patient-determined outcome scores, range of motion, and strength.

METHODS
Prior to initiation of this study, institutional review board approval was obtained (Avera 2008.009). Informed consent was obtained from all subjects and the rights of the subjects were protected. Forty-eight study subjects were obtained from a database that has been reported in a previous publication on patients enrolled in a randomized trial evaluating the efficacy and safety of pulley exercises after rotator cuff repair.22 Baseline data for demographic, preoperative range of motion and strength testing and magnetic resonance imaging findings are described in Table 1. Concomitant procedures and number of anchors used in the repairs are described in Table 2.

The inclusion criterion was patients undergoing immediate post-operative rehabilitation for an arthroscopic supraspinatus repair between October 2008 and November of 2012. Patients undergoing concomitant procedures such as subacromial decompression, distal clavicle resection, subscapularis repair, and biceps tenodesis were also included to increase the generalizability of this study since it is common clinically to perform combined procedures. Exclusion criteria were: patients with a history of previous rotator cuff repair on the ipsilateral or contralateral sides, concomitant preoperative adhesive capsulitis, history of glenohumeral dislocation, axillary or suprascapular neuropathy, cognitively impaired patients, and patients with subjective pain, weakness, or dysfunction on the contralateral side, and patients with less than one-year follow-up. All patients followed a comprehensive physical therapy protocol that was supervised by one of two physical therapists with significant experience in treating shoulder pathology both nonoperatively and postoperatively (RO, MJZ) [Appendix A].

The outcomes measures utilized for this study included patient-determined outcome scores, identification and quantification of scapular substitution, active range of motion, and strength. The independent observer that recorded scapular substitution,
range of motion, and strength was blinded to the patients-determined outcome scores to decrease bias. The patient outcome scores utilized in this study included the Western Ontario Rotator Cuff Index (WORC), Simple Shoulder Test (SST), the American Shoulder and Elbow Score (ASES), the Shoulder Activity Level, and the Single Alpha-numeric Evaluation (SANE). These outcome scores were collected at baseline, 6 weeks, 12 weeks, 18 weeks, 6 months, and 12 months.

In this study, scapular substitution was measured using both a subjective technique and an objective technique. The subjective scapular substitution measurement was performed by a physical therapist that answered a yes or no question if they felt that a patient had visually apparent scapular shrug (vertical and/or medial translation of the scapula) with scaption. The objective scapular substitution was determined using a previously published technique. This method has been shown to have good inter-rater reliability (ICC = 0.81) when measuring

<table>
<thead>
<tr>
<th>Table 1. Baseline demographic data, range of motion, motor strength and magnetic resonance imaging findings.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Patients</strong></td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>Mean Age</td>
</tr>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Dominant Hand</td>
</tr>
<tr>
<td>Traumatic Onset</td>
</tr>
<tr>
<td>Worker’s Compensation</td>
</tr>
<tr>
<td>Preoperative External Rotation</td>
</tr>
<tr>
<td>Preoperative Flexion</td>
</tr>
<tr>
<td>Preoperative Mean Muscle Strength</td>
</tr>
<tr>
<td>Supraspinatus</td>
</tr>
<tr>
<td>Intraoperative External Rotation</td>
</tr>
<tr>
<td>Intraoperative Flexion</td>
</tr>
<tr>
<td>Intraoperative Mean Outerbridge Grade</td>
</tr>
<tr>
<td>Presence of Supraspinatus Atrophy</td>
</tr>
<tr>
<td>Goutallier Changes</td>
</tr>
<tr>
<td>Grade 0</td>
</tr>
<tr>
<td>Grade 1</td>
</tr>
<tr>
<td>Grade 3</td>
</tr>
<tr>
<td>Supraspinatus Retraction</td>
</tr>
<tr>
<td>Within 1 cm Greater Tuberosity</td>
</tr>
<tr>
<td>Midhumeral</td>
</tr>
<tr>
<td>Glenohumeral</td>
</tr>
</tbody>
</table>

Table 2. Concomitant Procedures and Number of Anchors Utilized.

| Patients | Infra- | Subscapularis Repair | Acromioplasty | AC Joint Resection | Labral Repair | Biceps Debridement for Rupture | Biceps Tenodesis | Biceps Tenotomy | Coracoplasty | Excision Os Acromiale # of Medial Anchors |
|----------|-------|----------------------|---------------|-------------------|--------------|-------------------------------|-----------------|----------------|-------------|----------------|----------------------------------------|
|          | 1     | 10                   | 47            | 24                | 2            | 4                            | 14              | 4              | 2           | 1                          |

<table>
<thead>
<tr>
<th>Patients</th>
<th># of Medial Anchors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Patients</th>
<th># of Lateral Anchors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>
two-dimensional scapular translation during scaption. Each study subject had a marker placed on each acromion and stood a standardized distance from a light. The shadow projected from the marker onto a standardized, data collection board was measured during the 1) resting, and 2) scaption to 90 degrees positions for bilateral shoulders. The horizontal (medial) and vertical (superior) translations of the shadows were measured and compared to the resting point for scaption. For this current study, the objective absolute vertical and medial scapular measurements and the subjective scapular substitution measurements were recorded at the 12 week, 18 week, 6 month, and 12 month post-operative time (post-op) time points. In addition, the difference in side-to-side scapular measurements was reported by subtracting the vertical scapular translation of the nonoperative, asymptomatic side from the absolute vertical scapular translation of the operative side.

Range of motion assessments were performed with a standard goniometer with the patients in the standing position with their back resting against a wall. Active forward elevation, external rotation in 90 degrees of abduction, internal rotation in 90 degrees of abduction, and abduction were measured for both the operative and nonoperative arms at the 6 month and 12 month post-op time points.

Strength assessment was performed using a handheld dynamometer. Isometric scaption strength was tested in both the “empty can” and the “full can” positions for both the operative and nonoperative shoulder at the 6 month and 12 month time points. Strength was not tested prior to 6 months post-op to allow for appropriate rotator cuff tendon healing and to allow the effects of the strengthening protocol of the rehabilitation to manifest. Strength outcomes were reported as a ratio of operative side to nonoperative side since baseline strength testing was not determined. This method was considered acceptable since patients with contralateral shoulder symptoms or a history of contralateral shoulder surgery were excluded.

Statistical analyses were conducted using SAS 9.4 and included mixed model (2 between x 4 within) split plot ANOVAS (PROC MIXED) to test trends (linear trends whose slope differs from zero across time) and t-tests to determine differences between groups from baseline to 12 months post-surgery. A Chi-square test was used to examine categorical variables, and the Cochrane-Armitage test was utilized to determine trends. The level of significance was \( p = 0.05 \). Since multiple hypotheses were tested, effect sizes (Cohen's \( d \)) with 95% confidence intervals were calculated to determine the size of the differences between groups (Cohen's \( d \) 0.2 = small effect, Cohen's \( d \) 0.5 = medium effect, Cohen's \( d \) 0.8 = large effect).^{30,31}

**RESULTS**

The proportion of patients exhibiting subjective scapular substitution decreased significantly from 82% to 35% (\( \chi^2 = 21.38, p<0.0001 \)) through their first year following rotator cuff repair. This represents a greater than 50% relative reduction in subjective scapular substitution (Figure 1). This finding was confirmed using the absolute objective scapular substitution measurements which showed significant negative trends (slope) in both vertical (\( p = 0.04 \)) and medial (\( p = 0.01 \)) scapular translation during scaption (Figure 2). In addition, repeated measures ANOVAs revealed significant negative effect (i.e. slope) across time for the differences between operative and nonoperative shoulders' objective vertical translation (\( p < 0.0001 \)) and medial translation (\( p = 0.01 \)) during scaption (Figure 3).

At all post-operative time points, the operative side had greater absolute vertical scapular translation relative to the nonoperative side. The proportion of patients subjectively observed to have the presence of Scapular Substitution by a physical therapist (Yes/No).
Subjective scapular substitution is associated with objective scapular substitution. Patients with subjective substitution had a mean vertical side-to-side difference of 1.62 centimeters and absolute vertical translation of 5.15 cm. Those without subjective substitution had a significantly smaller mean 1) vertical side-to-side difference (0.36 cm; p<0.0001) and 2) absolute vertical translation (3.41 cm; p<0.0001).

At all post-operative time points, patients with subjective substitution had inferior WORC, ASES, SANE, and SST scores compared to patients without subjective substitution. These differences were statistically significant at the 18-week time point for the WORC and the ASES, 18 week and one year time point for the SANE, and the year time point for the SST (Figure 4). There were no clinical or statistical differences in the Shoulder Activity Level for those with subjective substitution compared to those without subjective substitution at any time point.

At all post-operative time points, patients with subjective scapular substitution had less flexion, abduction, and external rotation active range of motion compared to patients without subjective scapular substitution. These differences reached statistical significance for both flexion and external rotation at both the 6- and 12-month time points (p=0.007 and p=0.001, respectively), and for abduction at the 12-month time point (p=0.04) [Figure 5]. There was no clinical or statistical difference in internal rotation between patients with subjective substitution and those without substitution at the 6-month time point (52º vs 54º; p=0.72) and the 12-month time point (57º vs 59º; p=0.61).

At all post-op time points, patients with subjective scapular substitution had inferior empty can and full can scaption strength compared to those patients without subjective scapular substitution. These differences reached statistically significant differences at the 6-month time point for empty can scaption strength (p=0.03) and the 12-month time point for full can scaption strength (p=0.01) (Figure 6).

At the 12 month point the strength of patients without scapular substitution approximated that of the contralateral, unaffected side (empty can; p=0.17) (full can; p=0.18) suggesting that their strength returned to pre-injury status at 12 months post-op.

during scaption compared to the asymptomatic, nonoperative side (Figure 2). The operative side had statistically greater absolute medial translation with scaption at the 12 week and the 6 month time points (Figure 2).

Figure 2. Objective Absolute Scapular Translation with Scaption. Each study subject had a marker placed on the acromion of both shoulders and stood a standardized distance from a light. The shadow projected from the marker onto a standardized, data collection board was measured during the 1) resting, and 2) scaption to 90 degrees positions for both the operative and nonoperative shoulders. The horizontal (medial) and vertical (superior) translations of the shadows were measured and compared to the resting point for scaption for both shoulders.

Figure 3. Side to Side Difference in Scapular Translation with Scaption. The difference in side-to-side scapular measurements was reported by subtracting the objective absolute scapular translation of the nonoperative, asymptomatic side from the objective absolute scapular translation of the operative side.
DISCUSSION

The results of this study demonstrated that rotator cuff repair rehabilitation decreases but does not normalize objective scapular substitution. In addition, the results indicate that patients with subjective scapular substitution had inferior patient-determined outcome scores, range of motion, and strength compared to patients that did not have subjective scapular substitution.

Studies that examine if postoperative rehabilitation after rotator cuff repair can improve scapular kinematics are rare. This appears to be the first study to examine the association between scapular substitution and patient outcomes after rotator cuff repair. Patients identified with subjective scapular substitution had inferior patient outcome scores (except the Shoulder Activity level), decreased flexion, abduction, and external rotation active range of motion, and decreased scaption strength when compared to patients without scapular substitution. These findings are similar to those of Harris et al. who found an association with the presence of subjectively-determined scapular dyskinesis with a decrease in WORC index and ASES scores of 6.85 and 4.07, respectively, in patients that were identified as having full thickness rotator cuff tears.

In a study of patients with adhesive capsulitis and osteoarthritis, Fayad et al suggested that the scapulohumeral rhythm of the affected shoulder was inversely related to the severity of the limitation of shoulder range of motion. Kontaxis et al. suggested that reverse total shoulder arthroplasty patients with good recovery and large range of humeral elevation after surgery had a small change in their scapular rhythm whereas those with muscle weakness and smaller ranges of motion had greater amounts of...
scapular kinematic alterations. However, neither of these studies utilized validated, patient-determined outcome scores or quantitatively or qualitatively examined the strength of the subjects.

Previous studies have found altered shoulder kinematics including scapular elevation in patients with impingement and rotator cuff tears. Mell et al. reported that individuals with full thickness rotator cuff tears were more likely to have greater scapular elevation with arm elevation than in asymptomatic shoulders or in patients with tendinosis but no full thickness tears. The authors of that study admitted that their study was not designed to determine a relationship between these motion patterns with symptoms or function in rotator cuff patients and suggested future studies were needed to determine their effects. Scibek et al. demonstrated a trend toward improved scapulohumeral

Figure 5. Active Range of Motion and Subjective Scapular Substitution.

Figure 6. Scaption Strength and Subjective Scapular Substitution
E.C. = Empty Can Scaption Strength; F.C. = Full Can Scaption Strength
rhythm after a subacromial injection performed in patients with full thickness rotator cuff tears suggesting that pain is a potential cause of impaired scapular kinematics.\textsuperscript{14,17}

It is unknown if scapular substitution is an adaptive mechanism that assists patients with glenohumeral dysfunction or if it is part of a pathologic process that affects patient outcomes. Several studies demonstrated that altered scapular kinematics may result as a patient attempts to avoid impingement and the scapula becomes rotated to a greater degree to reduce the requirement for the elevation of the glenohumeral joint.\textsuperscript{2,16,33,36} Scibek et al suggested that these scapular substitution patterns are a method of compensating for pain and when pain was decreased, the scapular kinematics improved.\textsuperscript{17} Lukasiewicz et al. presumed that increased scapular elevation is a compensatory pattern that may be secondary to weakness or restricted range of motion because of capsular tightness, which may also increase scapular elevation.\textsuperscript{3} On the contrary, other studies demonstrated that altered scapula kinematics could reduce the available subacromial space, thus contributing to development or progression of impingement as well as a poor environment for tissue healing.\textsuperscript{11, 37} Mell et al. concluded that it was impossible to determine from their study if the altered scapular kinematics was a useful adaptation of a pathologic pattern that contributed to pain and dysfunction.\textsuperscript{16} Ludewig et al suggested that without the ability to follow human subjects longitudinally, it is difficult to fully discern if alterations found in scapular kinematics are compensatory or contributory to an impingement mechanism of rotator cuff disease.\textsuperscript{11}

Unfortunately, the current study was not designed to determine if scapular substitution is a cause of inferior patient outcomes or an effect of inferior patient outcomes. However, the findings of this study suggest that scapular substitution is either 1) a pathologic process or 2) a compensatory process that is inferior to normal scapular kinematics in regards to patient-determined outcome scores of pain and function, range of motion, and strength when following the rehabilitation of patients up to a year after a rotator cuff repair.

One previous study demonstrated that with verbal instruction patients had decreased mean scapular vertical displacement with forward elevation.\textsuperscript{5} However, no differences were found in horizontal displacement after instruction. The current study did reveal both decreased objective vertical and medial translation of the scapula during scaption with rehabilitation over a one-year period. Although both subjective and objective scapular substitution was decreased, the rehabilitation program that was utilized over this time did not normalize scapular kinematics. Future studies will be necessary to determine if a postoperative rehabilitation protocol that focuses on elimination of scapular substitution (possibly by decreasing upper trapezius activation and increasing serratus anterior and lower trapezius activity)\textsuperscript{6, 10} as an outcome can normalize scapular kinematics and improve patient outcomes.

The current study was limited by the lack of baseline scapular translation measurements. To control for this, patients with contralateral shoulder pain, dysfunction, or history of surgery were excluded, and contralateral scapular motion was tested on the non-operative extremity to use as a comparison. Other studies support this methodology as an appropriate means of comparing scapular kinematics over time.\textsuperscript{3,34} Another limitation was that 3-D measurement of scapular kinematics was not utilized. However, at this time, there is no universally accepted, gold standard for a clinical method for identifying subjects that may have abnormal scapular kinematics. However, the technique that was utilized was previously validated and has been shown to have good reliability for measuring scapular translation with scaption and is suitable for routine clinical use.\textsuperscript{4,14,28,29} Lastly, it was difficult to quantify the amount of compliance to the home rehabilitation protocol for each patient. However, there was no evidence that any patient was subjectively “noncompliant” with the home rehabilitation recommendations.

CONCLUSION

The findings of the current study indicate that rehabilitation decreases but does not normalize the amount of scapular substitution up to one year after rotator cuff repair. The presence of subjective visual identification of scapular substitution is associated with inferior patient-determined outcome scores (WORC, ASES, SST, SANE), active range of motion (flexion, external rotation, abduction), and scaption strength.
REFERENCES


SUPPLEMENTAL APPENDIX A. POSTOPERATIVE PHYSICAL THERAPY PROTOCOL

Rotator Cuff Rehabilitation Protocol

Maximum Protection Phase: 0-3 Weeks Post-Op

Goals:
- Permit early healing to occur without affecting repair
- Begin recovering shoulder range of motion within pain free range
- Ensure elbow, wrist and hand range of motion is maintained at pre-operative level

Protection
- Sling immobilization at all times unless performing personal hygiene or exercises

Rehabilitation program

Joint Range of Motion activities
- Range of motion activities (performed 3-5 x daily)
  - Pendulum exercises to be performed in sagittal and transverse planes
  - Passive supine elevation with therapist or with spouse/significant other after instruction or with opposite hand or performed seated at table
  - Passive external rotation with therapist or with spouse/significant other after instruction or with wand in sitting or performed in sitting performing external rotation at a table.
  - Hand, wrist, elbow range of motion and progressive resistive exercises (unless biceps tenodesis performed)

Muscle activation (performed 2x daily)
- Scapular active range of motion / isometric / stabilization exercise in protective range – for scapular elevation, protraction, retraction, depression (pain free)
- Deltoid isometrics - submaximal and pain free in neutral at glenohumeral joint.

Moderate Protection Phase: 4-5 Weeks Post-Op

Goals:
- Continue to protect the repair to permit optimal healing
- Continue with recovering pain free shoulder range of motion
- Ensure elbow, wrist and hand range of motion is maintained at pre-operative level

Protection
- Sling immobilization at all times unless performing personal hygiene or exercises

Rehabilitation Program

Joint Range of Motion activities
- Continue above exercises progressing range of motion to tolerance (3-5 x daily), and add the following:
  - Supine wand exercises for flexion
  - Seated (arm at the side) or supine (arm in slight abduction supported on bolster) external rotation low load stretching with wand to end range.
  - May initiate hydrotherapy (pool exercises) active assisted range of motion once incisions heal

Muscle activation activities (2x daily)
- ER / IR pain free submaximal isometrics at glenohumeral joint neutral (shoulder not in extension)
- Progress pain free deltoid isometric exercise as tolerated
- Weight shifts using table/counter or exercise ball

Early Strengthening Phase: 6 – 14 weeks Post-Op

Goals:
- Recover full shoulder range of motion
- Recovery of low level functional activity
- Initiate recovery of muscle strength to include rotator cuff
Protection

- Discontinue sling use (may still use sling when in crowded areas)

Rehabilitation Program

INITIATE JACKINS EXERCISE VS PULLEY EXERCISES PER GROUP ASSIGNMENT

Joint Range of motion activities

- Continue to progress range of motion exercises to tolerance (2-3 x daily)
  - Flexibility exercises adjusted to address areas of tightness
  - Joint mobilization to address any residual capsular tightness

Muscle activation activities

- Initiate humeral head stabilization exercises (1-2 x daily)
  - Begin active isotonic exercises for external rotation at glenohumeral joint neutral and progress to gentle resistance band exercises (side-lying external rotation)
  - Begin active isotonic exercises for internal rotation with glenohumeral joint neutral and progress to gentle resistance band strengthening (standing internal rotation with arm at the side and elbow flexed to 90 degrees provides good activation of subscapularis and pectoralis major muscles with low to medium resistance)
  - Incorporate rhythmic stabilization activities

- Scapular exercises (1-2x daily) (should be performing at least 15 repetitions of each exercise)
  - Continue scapular stabilization exercises by performing scapular clock exercises
    - Advance to low level closed chain activities as tolerated (pain free) by performing either prone on elbows or quadruped (on knees) push up plus as able
    - Perform scapular adduction in sitting and/or prone
      - Active scapular adduction without resistance
      - Resisted scapular adduction via resisted shoulder extension with elastic tubing
      - Prone rowing exercise
    - Perform scapular adduction in sitting and/or prone (continued)
      - Prone horizontal abduction with arm elevated to 100 degrees if can achieve without discomfort. Hand position with thumb up if able to perform, but if not, palm parallel to floor is acceptable.
      - Begin exercises focused on scapular depressors (pectoralis major, latissimus dorsi and teres major)
        - When shoulder elevation is adequate, begin performing pull down exercise with arms in front of body with wide (shoulder width) grip (provides best activation of latissimus dorsi and teres major muscles)
        - Low level activation of the pectoralis major occurs in the quadruped weight bearing position. The activation increases as the individual performs a tripod position (both knees and involved arm in contact with surface). Pushup position with feet on a bench and one arm pushup position are not appropriate at this time.

- Additional muscle activation (1-2 x daily)
  - Deltoid (flexion and abduction) isometrics at 30 degrees elevation
  - Other deltoid muscle activation activities
    - Supine shoulder flexion provides activation of anterior deltoid
    - Seated or standing active elevation for anterior deltoid (monitor scapular elevation)
    - Prone horizontal abduction with arm in 100 degrees elevation (as able) with hand supinated (as able) provides best activation of posterior deltoid.
  - Include biceps brachii and triceps brachii strengthening in a progressive resistive exercise program

- Upper body ergometry (daily or as equipment is available)
Late Strengthening Phase: 14-22 Weeks Post-Op

Goals:
• Maintain full shoulder range of motion
• Recovery of intermediate level functional activity
• Advance muscle strengthening resistance activities

Rehabilitation Program

Joint Range of Motion Activities
• Continue to progress range of motion and flexibility (1-2 x daily)
• Address any remaining capsular tightness with joint mobilization
• Address any muscle length issues with appropriate stretching activities.

Muscle activation activities
• Progress resistance to 12-15 repetitions and 2 sets for each exercise
• Progress rotator cuff isotonics as tolerated (1x daily as able or every other day as appropriate)
  ▪ May perform upright resistive band scaption exercises (full can) when able to perform upright active forward elevation to 130 degrees
• Upper extremity progressive resistive exercises for large muscle groups; pectoralis, latissimus dorsi (1x daily)
• Initiate plyometric exercises below horizontal (1x daily as able, or every other day as appropriate)
• Advance scapular stabilization strengthening activities to intermediate level as tolerated (1x daily)
  ▪ Increased weight bearing in quadruped position by lifting non-operative arm forward (must be pain free)

Return to Sport Phase: 22-28 Weeks Post-Op

Goals:
• Maintain full shoulder range of motion
• Recovery of high level functional activity to include throwing activities
• Performance of high level strengthening and resistance activities

Rehabilitation Program

Joint Range of Motion Activities
• Should have full joint range of motion. If does not, address with joint mobilization and specific stretching activities.

Muscle activation activities
• Should be performed with resistance such that person is performing 10-12 repetitions for each exercise without shoulder joint discomfort on an every other day basis (2-3x per week has been found to be optimal in strength literature)
• Aggressive upper extremity progressive resistive exercises – internal and external rotation isokinetics, velocity spectrum on individual basis (every other day).
• High level scapular stabilization activities (every other day)
  ▪ Push up position
  ▪ Push up position while lifting non operated arm
  ▪ Weight bearing on small plyoball in various positions
  ▪ Perturbations while weight bearing on plyoball
• Progress plyometrics to include throwing activities (every other day): for subjects who wish to return to throwing activities
ABSTRACT

Background: The scapula is a critical link utilized in the kinetic chain to achieve efficient overhead movement and transfer energy from the lower extremity to the upper extremity. Additionally, daily activities such as sitting at a computer or driving in a car may negatively influence an individual's ability to maintain proper body posture and therefore compromise those movements. To reduce these negative influences, posture garments have been designed to cue the individual in maintaining and improving posture and alignment, specifically targeting scapular positioning.

Purpose: The purpose of this study was to compare scapular positioning between an IntelliSkin™ posture-cueing compression garment and a generic performance garment on scapular kinematics during static standing.

Study Design: Case control.

Methods: Forty active females (1.68 ± 0.07 m; 67.29 ± 11.25 kg) stood in a natural standing position while wearing two different garments: IntelliSkin™ posture-cueing compression garment and a generic performance garment. Kinematic data were collected at 100 Hz using an electromagnetic tracking system (trakSTAR™, Ascension Technologies, Inc., Burlington, VT, USA) synced with The MotionMonitor® (Innovative Sports Training, Chicago, IL., USA).

Results: Repeated measures ANOVAs revealed a statistically significant Shirt by Side interaction for scapular protraction/retraction (F(1,39) = 52.91, p ≤ 0.05) and main-effect of Shirt for scapula anterior/posterior tilt (F(1,39) = 96.45, p ≤ 0.05). Individuals showed increased retraction and posterior tilt while wearing the IntelliSkin™ posture-cueing compression garment.

Conclusion: The results of the current study indicate that the IntelliSkin™ posture-cueing compression garment improved scapular positioning during static standing posture. The IntelliSkin™ posture-cueing compression garment may provide clinicians an adjunct strategy to include with rehabilitative protocols.

Level of Evidence: Diagnosis, Level 3

Key Words: Kinetic chain, proprioceptive feedback, rehabilitation, scapular kinematics, upper extremity kinematics
INTRODUCTION
The body is designed for locomotion; however, specific daily activities, such as sitting at a desk for an extended period and prolonged screen use may negatively influence an individual's ability to maintain proper body posture and therefore compromise their movements. Excessive sitting posture influences the alignment on the entire axial skeleton which can ultimately have a negative impact on standing posture and the ability of the upper and lower extremities to efficiently move during locomotion. This posture is consistent with concepts described by Grimsby and Gray have stated that individuals with the classic forward head, rounded shoulders, and increased thoracic kyphosis, have scapulae that rotate forward and downward depressing the acromion process and thus decreasing the subacromial space. This may lead to alterations during overhead movement and impingement of the soft tissues in the subacromial space. Individuals displaying this posture have altered scapular positioning and kinematics, which is often referred to as 'scapular winging,' 'scapular dyskinesia,' or 'scapular dyskinesis' and may or may not be associated with the symptom of pain.

The scapula is a critical link utilized in the kinetic chain for human movement. It must function in both stabilization and mobilization for efficient glenohumeral movement, as well as serve as a vital link in the kinetic chain. As a dynamic mover of the upper extremity, the scapula functions in protraction and retraction, upward and downward rotation, anterior and posterior tilt, and elevation and depression. Additionally, as a glenohumeral joint stabilizer, the scapula is a base of support for muscle attachment to allow free motion to occur about the glenohumeral joint.

To combat the decline in optimal posture and scapular positioning, physical therapists and athletic trainers have used different taping methods, as well as worked with apparel companies to design posture-cueing compression garments and shoulder and trunk braces. These garment designs aim to cue the individual in maintaining and improving posture and alignment, specifically targeting the posterior shoulder region to influence scapular positioning and thus attempt to restore normal shoulder kinematics. Proper posture is defined as the muscular balance which protects the supporting structures of the body against injury or progressive deformity, while poor posture is defined as a faulty relationship of the various parts of the body which produce increased strain on the supporting structures causing decreased efficiency of balance of the body over its base of support. Postural garment designs have been assessed in several studies focusing on alterations in proper posture such as the forward shoulder posture. Cole et al. found that shoulder posture significantly improved when participants wore a scapular-stabilizing compression garment with increased tension on the straps, as compared to the control compression garment that did not include tension straps. Additionally, Ulkar et al. suggested that application of compressive bracing enhances the position of the shoulder complex by increasing the sensation of stability.

Other postural-cueing compression garments, such as IntelliSkin™, are specifically designed to signal posture and core musculature to activate and attempt to align an individual's shoulders, spine, and trunk. The posture-cueing technology in combination with the compression material mimics the effects of Kinesiology Tape (KT) to assist the body in postural control. The IntelliSkin™ posture-cueing compression garment has been shown to provide clinical success among athletes by positively altering athletic performance and reducing injury. During an unpublished longitudinal study presented at the American Orthopaedic Society of Sports Medicine annual meeting, Shepard et al. revealed that over a course of two seasons an improvement in scapular retraction and no days of competition were lost due to injury among National Collegiate Athletic Association (NCAA) Division I male volleyball athletes. Additionally, cyclists who wore the IntelliSkin™ posture-cueing compression garment perceived positive benefits for riding posture, post-ride posture, spine discomfort, and post-ride recovery. With the need for proper posture as well as proper scapular kinematics during overhead movements, the purpose of this study was to determine the effectiveness of an IntelliSkin™ posture-cueing compression garment compared to a generic performance garment on scapular kinematics during standing.
To the authors’ knowledge, analysis of scapular positioning while wearing an IntelliSkin™ posture-cueing compression garment compared to a generic performance garment has yet to be evaluated. This preliminary study attempted to determine if static scapular positioning can be influenced by a posture-cueing compression garment. It was hypothesized that the IntelliSkin™ posture-cueing compression garment would improve scapular positioning among active females in the directions of scapular retraction, upward rotation, and posterior tilting.

METHODS
A convenience sample of forty active females (20.7 ± 1.33 yr; 1.68 ± 0.07 m; 67.29 ± 11.25 kg) were recruited to participate. IntelliSkin™ provided female posture-cueing compression garments of varied sizes to serve the participant sample. Participants who reported having any upper extremity injury within the prior six months were excluded. The Institutional Review Board of Auburn University approved all testing protocols and informed consent was obtained prior to any testing.

This was a validation study in a controlled laboratory setting with the objective of comparing scapular position between the IntelliSkin™ posture-cueing compression garment and a generic performance garment. The independent variable for this study was shirt type while the dependent variables were scapular kinematics of retraction, upward rotation, and posterior tilt.

Testing required the participants to stand while wearing two different garments. Participants were verbally instructed to position themselves in a natural standing position as if they were standing in line with hands by side and looking forward. Once the participant was in a natural stance, data were recorded in two conditions: wearing the IntelliSkin™ posture-cueing compression garment (Figure 1) and wearing a generic performance garment (Figure 2). Participants wore each garment only for the period of time it took to collect them standing in a natural standing position. This position was approximately 1-minute for each condition with a 3-minute time difference between testing each garment.

Kinematic data were collected at 100 Hz using an electromagnetic tracking system (trakSTAR™, Ascension...
Technologies, Inc., Burlington, VT, USA) synced with The MotionMonitor® (Innovative Sports Training, Chicago, IL, USA). Participants had a series of 11 electromagnetic sensors affixed to the skin, under their garment, using PowerFlex cohesive tape (Andover Healthcare, Inc., Salisbury, MA) to ensure the sensors remained secure throughout testing. Sensors were attached to the following locations: (1) posterior aspect of the torso at the first thoracic vertebrae (T1) spinous process; (2) posterior aspect of the pelvis at the first sacral vertebrae (S1); (3) top of the head; (4-5) flat, broad portion of the acromion, bilaterally; (6-7) lateral aspect deltoid tuberosity, bilaterally; (8-9) posterior aspect of bilateral distal forearm, centered between the radial and ulnar styloid processes; and (10-11) lateral aspect of each thigh, centered between the greater trochanter and the lateral condyle of the knee. A twelfth, moveable sensor was attached to a plastic stylus used for the digitization of bony landmarks. To ensure accurate identification and palpitation of bony landmarks, the participant stood in anatomical neutral throughout the duration of the digitization process. Using the digitized joint centers for hips, shoulders, T12-L1, and C7-T1, a link segment model was developed. Joint centers were determined by digitizing the medial and lateral aspect of a joint then calculating the midpoint between those two points. The spinal column was defined as the digitized space between C7-T1 and T12-L1. A rotation method, validated as capable of providing accurate positional data was utilized to estimate the joint centers of the shoulders and hips. The shoulder joint centers were calculated from the rotation of the humerus relative to the scapula while the hip joint centers were calculated from the rotation of the femur relative to the pelvis. The rotation method consisted of the investigator stabilizing the joint then passively moving the limb into six different positions in a small, circular pattern. Raw data regarding sensor position and orientation were transformed to locally based coordinate systems for each of the representative body segments. For the world axis, the y-axis represented the vertical direction; horizontal and to the right of y was the z-axis; anterior and orthogonal to the plane defined by y and z was the x-axis. Position and orientation of the body segments were obtained using Euler angle decomposition sequences for the motion of the scapula relative to the thorax (Y-X-Z order). Kinematic data were obtained using Euler angle sequences, consistent with the International Society of Biomechanics standards and joint conventions. All raw data were independently filtered along each global axis using a 4th order Butterworth filter with a cutoff frequency of 13.4 Hz. All data were time stamped through The MotionMonitor® and passively synchronized using a data acquisition board.

All statistical analyses were performed using IBM SPSS Statistics 22 software (IBM Corp., Armonk, NY) with an alpha level set a priori at $\alpha = 0.05$. Prior to analysis, Shapiro-Wilk Tests of Normality were run. Results showed an approximately normal distribution of the standing static posture data. All kinematic variables of the standing static posture in two conditions were analyzed using a 2 (Shirt) x 2 (Side) repeated measures analysis of variance (ANOVA). This ANOVA was applied to the variables of scapula protraction/retraction, upward/downward rotation, and anterior/posterior tilt. For all variables, Mauchly’s Test of Sphericity was conducted prior to all analyses, and a Greenhouse-Geisser correction was imposed when sphericity was violated. Paired sample t-tests were used to further examine differences when statistically significant effects were seen.

## RESULTS

Means and standard deviations (SDs) for each kinematic variable for the static standing posture are reported in Table 1. Repeated measures ANOVAs of all scapula kinematic variables are revealed in Table 2 and indicate a significant main effect of Shirt for scapula anterior/posterior tilt and a statistically significant Shirt by Side interaction of scapular protrac-tion/retraction. Post-hoc test results are shown in Table 3. There were no statistically significant scapula upward/downward rotation interactions.

## DISCUSSION

The purpose of this study was to determine the effectiveness of an IntelliSkin™ posture-cuing compression garment compared to a generic performance garment on scapular kinematics during static standing. It was hypothesized that IntelliSkin™
posture-cueing compression garment would improve scapular positioning among the female participants. Significant kinematic differences were observed in the natural standing condition in scapular protraction/retraction and anterior/posterior tilt. The participants in the current study presented with greater retraction and posterior tilt while wearing IntelliSkin™ posture-cueing compression garment compared to the control garment. The position of posterior tilt allows for elevation of the acromion and in overhead athletes this position has proven beneficial. Positioning the scapula in retraction allows for an efficient transfer of energy from eccentric to concentric for explosive acceleration in dynamic overhead movements. Additionally, posterior tilt and upward rotation allows movement of the arm to clear the acromion during forward elevation or abduction. Kibler et al. and Myers et al. described the necessity of the scapular retraction position during overhead movements as it allows maximum activation of all muscles, which assist the scapula to maintain a stabilized position. Therefore, it is postulated that by wearing the IntelliSkin™ posture-cueing compression garment an individual may benefit from an improved position of the scapula during static

<table>
<thead>
<tr>
<th>Variables</th>
<th>Control Garment</th>
<th>Posture-Cueing Garment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapular Protraction/Retraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>1.59 (5.23)</td>
<td>-5.34 (10.61)</td>
</tr>
<tr>
<td>Left</td>
<td>-2.92 (4.86)</td>
<td>3.34 (6.17)</td>
</tr>
<tr>
<td>Scapular Up/Down Rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>-0.53 (4.30)</td>
<td>-2.18 (4.90)</td>
</tr>
<tr>
<td>Left</td>
<td>0.02 (3.72)</td>
<td>-0.19 (6.71)</td>
</tr>
<tr>
<td>Scapular Anterior/Posterior Tilt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>2.7 (4.05)</td>
<td>13.2 (6.82)</td>
</tr>
<tr>
<td>Left</td>
<td>3.84 (5.48)</td>
<td>13.75 (11.56)</td>
</tr>
</tbody>
</table>

Note: Scapular protraction (+)/retraction (-), scapular up (+)/down (-), scapular anterior (-)/posterior (-)

### Table 2. Repeated measures ANOVAs of scapular positional kinematics.

<table>
<thead>
<tr>
<th></th>
<th>Scapular Protraction/Retraction</th>
<th>Scapular Up/Down Rotation</th>
<th>Scapular Anterior/Posterior Tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shirt</td>
<td>F(1,39) = 0.20, p = 0.67, r² = 0.01</td>
<td>F(1,39) = 1.75, p = 0.19, r² = 0.04</td>
<td>F(1,39) = 96.45, p ≤ 0.05, r² = 0.71</td>
</tr>
<tr>
<td>Side</td>
<td>F(1,39) = 1.70, p = 0.20, r² = 0.04</td>
<td>F(1,39) = 1.73, p = 0.20, r² = 0.04</td>
<td>F(1,39) = 0.61, p = 0.44, r² = 0.02</td>
</tr>
<tr>
<td>Shirt*Side Interaction</td>
<td>F(1,39) = 52.91, p ≤ 0.05, r² = 0.58</td>
<td>F(1,39) = 2.20, p = 0.15, r² = 0.05</td>
<td>F(1,39) = 0.13, p = 0.73, r² ≤ 0.01</td>
</tr>
</tbody>
</table>

### Table 3. Post Hoc Analysis of Scapular Protraction/Retraction and Scapular Anterior/Posterior Tilt.

<table>
<thead>
<tr>
<th></th>
<th>95% CI</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Garment Right vs Left</td>
<td>1.67, 7.36</td>
<td>3.21</td>
<td>p ≤ 0.01</td>
</tr>
<tr>
<td>Posture-Cueing Garment Right vs Left</td>
<td>4.26, 13.10</td>
<td>3.98</td>
<td>p ≤ 0.01</td>
</tr>
<tr>
<td>Control Garment vs Posture-Cueing Garment Right</td>
<td>4.12, 9.75</td>
<td>4.99</td>
<td>p ≤ 0.01</td>
</tr>
<tr>
<td>Control Garment vs Posture-Cueing Garment Left</td>
<td>-8.17, -4.34</td>
<td>-6.62</td>
<td>p ≤ 0.01</td>
</tr>
<tr>
<td>Control Garment vs Posture-Cueing Garment Right</td>
<td>-12.57, -8.43</td>
<td>-10.28</td>
<td>p ≤ 0.01</td>
</tr>
<tr>
<td>Control Garment vs Posture-Cueing Garment Left</td>
<td>-13.10, -6.72</td>
<td>-6.28</td>
<td>p ≤ 0.01</td>
</tr>
</tbody>
</table>
standing, which could possibly allow for more efficient positioning during overhead tasks.

Similarly, posterior tilting of the scapula has been shown to contribute to elevation of the anterior acromion, thereby decreasing compression of subacromial soft tissues during humeral elevation and abduction. For efficient arm elevation in dynamic upper extremity movements the scapula must posteriorly tilt to allow for acromial elevation. Since elevation allows for increased subacromial space for full arm elevation, if one is performing dynamic overhead movement without acromioclavicular elevation, there is a relative decrease (or lack of increase) in subacromial space and a greater susceptibility for impingement of the supraspinatus or biceps tendon. By eliciting greater scapular posterior tilt, the IntelliSkin™ posture-cueing compression garment appears to allow for elevation of the acromion that could possibly influence the effectiveness of dynamic movements. Subacromial impingement, which is associated with scapular dyskinesis, is one of the most commonly diagnosed injuries of the upper extremity and causes alteration in both dynamic and static scapular positioning. Although the focus of this study was not on the muscular activity during the wearing of the IntelliSkin™ posture-cueing compression garment, it is important to note that scapular positioning alterations are associated with muscle activation patterns and strength of scapular stabilizing muscles. Individuals with subacromial impingement have been found to have increased upper trapezius activation, decreased lower trapezius activation, and decreased serratus anterior activation, thus contributing to inadequate rotation and movement of the scapula. These muscular activation patterns cause excessive anterior scapular tilt and loss of upward rotation that may result in injury.

In addition, although this study found no significant difference between the garments in upward/downward rotation, it is important to note the IntelliSkin™ posture-cueing compression garment did show a non-statistically significant increase in upward rotation. Researchers have shown that upward rotation of the scapula is important for increasing subacromial space, thereby decreasing impingement of soft tissues. These improvements may suggest this posture-cueing compression garment assists in scapular proprioception, thus possibly providing biofeedback that could assist in improving static scapular posture.

As the posterior scapular stabilizing musculature works to retract, posteriorly tilt, and upwardly rotate, it is speculated that in turn there is a reduction in pectoralis minor tension and an increase in lower trapezius and serratus anterior activation. This improved length-tension relationship allows for repositioning of the acromion posteriorly to create more subacromial space and increase shoulder range of motion. Any alteration of scapular positioning in excessive protraction, downward rotation, or anterior tilt can cause pain and may lead to an increased risk of injury. Any pain associated with shoulder mobility may inhibit proper function of scapular movement and therefore lead to chronic shoulder impingement.

LIMITATIONS AND FUTURE RESEARCH

Limitations of this study include a female, undergraduate population. Although participants were healthy and reported not having an upper extremity injury within the prior six months, participants were not screened for scapular dyskinesis, which may have contributed to the greater variety (large standard deviations) of scapular positioning present in the statistical analysis.

Future research should focus on the implications the IntelliSkin™ posture-cueing compression garment has in a clinical setting among individuals suffering from scapular dyskinesis. Research should also examine the IntelliSkin™ posture-cueing compression garment influence on muscle activation of the shoulder complex and lumbopelvic-hip complex.

CONCLUSIONS

Proper posture and scapular positioning are necessary components to ensure appropriate coordination and efficiency of overhead movements. Any deviation from optimal posture and scapula positioning may increase upper extremity injury susceptibility during overhead tasks. The results of the current study indicate that the IntelliSkin™ posture-cueing compression garment improved scapular positioning during static standing posture. However, this study is a preliminary study and further investigation regarding the impact the IntelliSkin™ posture-cueing compression garment may have on scapular positioning during dynamic movements is warranted.
REFERENCES


10. Smith, S. S3 EFFECTIVE FOR SHOULDER PATHOLOGIES. (n.d.).


Reliability and Validity of the Halo Digital Goniometer for Shoulder Range of Motion in Healthy Subjects

Sarah Correll, PT, DPT
Jennifer Field, PT, DPT
Heather Hutchinson, PT, DPT
Gabby Mickevicius, PT, DPT
Amber Fitzsimmons, PT, DPTSc
Betty Smoot, PT, DPTSc, MAS

Background: Range of motion (ROM) of the shoulder is an integral component of assessment of musculoskeletal shoulder impairments. ROM is typically measured using a universal goniometer (UG). The UG has demonstrated good intra and inter-rater reliability for measuring shoulder ROM, although limitations exist. In recent years, alternative measurement devices such as smartphone applications and digital goniometers have been introduced, potentially addressing some of the shortcomings of the UG. Limited research is available on the validity and reliability of these alternative devices, including the laser-guided digital goniometer, in measuring shoulder ROM.

Purpose: The purpose of this study was to investigate the intra- and inter-rater reliability and concurrent validity of a laser-guided digital goniometer (HALO) for measuring active shoulder ROM.

Methods: A convenience sample of healthy volunteers was recruited. To be eligible, participants were required to be between 18 and 75 years of age and able to actively move at least one shoulder into 90° of glenohumeral abduction. Self-report of previous significant shoulder injury; previous shoulder surgery; current bilateral shoulder pain; current neck or upper back pain; or referred pain into the upper extremity were exclusion criteria. Active shoulder flexion, abduction, internal rotation, and external rotation were measured for each shoulder. Two evaluators measured each motion twice with each device (HALO and the UG) per shoulder. The intra-class correlation coefficient (ICC) for reliability and validity/agreement between devices was calculated using a two-way mixed model with a 95% confidence interval.

Results: Data were analyzed for 75 shoulders from 41 participants (seven participants had only one shoulder evaluated). Intra-rater reliability ICCs are between 0.82 and 0.91 for the HALO, and 0.83 to 0.95 for the UG. Inter-rater reliability for the HALO was 0.89 to 0.98 and for the UG was 0.90 to 0.98. The ICCs for agreement, comparing the HALO digital goniometer to the UG ranged from 0.79 to 0.99.

Conclusion: This study provides evidence that the HALO digital goniometer can be a reliable and valid tool for measuring shoulder ROM in individuals with healthy shoulders. However, the two devices should not be used interchangeably to evaluate a single individual's change over time for any motion.

Level of Evidence: Diagnostic Study (clinical measurement), Level 2b

Key Words: Clinimetrics, goniometry, reliability, shoulder, validity

CORRESPONDING AUTHOR
Betty Smoot, PT, DPTSc, MAS
Department of Physical Therapy and Rehabilitation Science
University of California San Francisco
1500 Owens St Suite 400
San Francisco, CA 94158
E-mail: betty.smoot@ucsf.edu
INTRODUCTION

The assessment of joint range of motion (ROM) is an important component of a physical therapy examination. These measurements are critical for providing baseline data, determining functional limitations, and monitoring changes in joint mobility in response to treatment. Measurement of ROM may also be used to detect asymmetry and movement restrictions that may increase risk of injury. While the universal goniometer (UG) has been considered the gold standard for clinical assessment of ROM, additional tools used in a clinical setting include inclinometers, digital goniometers, smartphone application-based tools, and laser-guided devices.

Universal goniometry is frequently used by physical therapists to assess ROM due to its ease of use, portability, noninvasive nature, and low cost. The UG is reported to have excellent inter-rater and intra-rater reliability for the assessment of upper extremity ROM. While studies that evaluate concurrent validity of the UG for assessment of upper extremity ROM are limited, the UG is used frequently in validation studies of alternative ROM measurement devices. However, there are limitations associated with its use: the UG requires two hands to manipulate the instrument, can be challenging to accurately position, and requires clear visual estimation for alignment and measurement-reading. These limitations could contribute to measurement error.

Thus, alternative ROM assessment tools, such as smartphone applications are gaining popularity in physical therapy practice settings, due to their low cost, availability, and ease and speed of use. Several studies have evaluated the reliability and validity of smartphone ROM applications. Mitchell et al. evaluated the reliability and validity of an iPhone goniometer for the assessment of active shoulder external rotation ROM and found that inter-rater reliability ranged from 0.92 to 0.94 and intra-rater reliability ranged from 0.79 to 0.81. When compared to universal goniometry, concurrent validity was 0.93 to 0.94. Johnson et al. reported that a smartphone magnetometer-based goniometer has equivalent reliability compared to a UG for passive shoulder abduction ROM, however, active shoulder ROM was not reported. However, the reliability of measurements across smartphones for the same application-based tool has not been evaluated. This limitation warrants consideration because individual therapists are likely to use their own smartphone in the clinical setting to evaluate ROM, rather than a clinic-provided tool. Additionally, the absence of guiding mechanisms in identifying bony landmarks during measurement may increase the potential for measurement error.

In contrast to smartphone application-based goniometers and the UG, the laser-guided digital goniometer utilizes lasers that intersect with anatomical landmarks, distal and proximal to the joint being measured. This feature reduces the need for the visual estimation required by smartphone applications and the relatively short arms of the UG. There is currently one device commercially available that uses lasers, as well as a magnetic system and accelerometers, to guide alignment with anatomical landmarks (HALO, model HG1, HALO Medical Devices, Australia). A single methodological study assessed reliability and validity of the HALO for active shoulder internal rotation (IR) and external rotation (ER) in 15 healthy participants (30 shoulders). Intra-rater reliability was excellent (ICC = 0.97–0.98). Concurrent validity, comparing the HALO to the inclinometer was also excellent (ICC = 0.97–0.98). These findings support use of the HALO for measuring active shoulder IR and ER ROM. However, there is a need for further research to confirm these findings, evaluate additional movements, and assess inter-rater reliability. Additionally, assessment of the agreement between the HALO laser-guided digital goniometer and the UG is warranted.

Therefore, the purpose of this study was to investigate the intra- and inter-rater reliability and concurrent validity of a laser-guided digital goniometer (HALO) for measuring active shoulder ROM. Active shoulder flexion, abduction, IR, and ER were examined in healthy adults. The results of this study will inform future research to compare reliability and validity among smartphone application-based goniometric tools, the HALO laser guided digital goniometer, and the UG. Rigorous methodological research is needed to ensure that joint range of motion measurements obtained with these new devices are consistent and accurate, in both research and clinical settings.
METHODS

Participants: A convenience sample of healthy volunteers was recruited from faculty, staff, and students of the University of California San Francisco/San Francisco State University Graduate Program in Physical Therapy, from October 2016 through January 2017. To be included in this cross sectional methodological study, participants had to be adults between 18 and 75 years of age; able to easily move between supine and standing positions; and able to actively move at least one shoulder into 90° of glenohumeral abduction. Exclusion criteria were self-report of previous significant shoulder injury; previous shoulder surgery; current bilateral shoulder pain; current neck or upper back pain; or referred pain into the upper extremity (i.e. cervical radiculopathy). Approval was received from the University of California, San Francisco Institutional Review Board prior to participant recruitment. All participants gave written informed consent. Participants completed a demographic questionnaire including information on age, income, ethnicity, activity status, occupation, health, and participant-reported height and weight.

Devices: Shoulder active range of motion (AROM) was assessed with the universal goniometer (UG) and the laser guided digital goniometer. UG: The universal mechanical goniometer (Baseline® Plastic Goniometer - HiRes™ 360 Degree Head - 12 inch arms) is a high-resolution plastic goniometer that permits observation of the axis of motion and ROM of the joint being measured. Laser-guided Digital Goniometer: The laser-guided digital goniometer (Halo, Halo Medical Devices, Subiaco, Western Australia) is a hand-held, pocket-sized (88mm x 88mm x 17mm), digital goniometer using low-level Class 1 laser technology to measure joint angles.

Assessors: Two third-year Physical Therapy doctoral students served as the assessors and another served as the recorder. The assessors received specific training in the use of the HALO device and the UG to measure shoulder AROM. Four third year doctoral physical therapy students independently reviewed the HALO instruction manual, online videos provided by the manufacturer's website, and current literature to develop study procedures. Training was provided by two full time faculty members with 15 and 30 years of clinical experience and who teach clinical examination skills (including goniometry) to physical therapy doctoral students. The student researchers and faculty members practiced the technique in group sessions for shoulder range of motion in the development of procedures through multiple sessions from April-June 2016, with instruction and training provided by the faculty members.

Assessors were blinded to the results of laser-guided digital goniometer for both the repeated tests (reliability) and the concurrent tests (validity). To prevent measurement bias, an index card was placed on the face of the HALO digital goniometer after the device was zeroed, and the measurement scribed by the study recorder. Excellent reliability of the standard goniometer has been established in previous studies, and evaluation of reliability, of the UG, while reported, was not the goal of this study. Therefore, the assessors were not blinded to the repeated measurements obtained with the UG.

Procedures: Step-by-step procedures for the range of motion assessment are outlined in Appendix 1. To reduce the risk of a mobilization effect from repeated shoulder movements, the first assessor personally demonstrated the desired movement (beginning with shoulder flexion), and then the participant performed a single return demonstration for that movement as a warm-up. The warm-up motion served two purposes: first, as a teaching tool for the participant to practice the ROM movement demonstrated by the assessor; and second, as an initial stretch through that ROM to minimize an increase in range obtained by repeated motions. After the warm-up, the participant performed the desired movement and maintained the end position for assessment by both assessors. Each device was used twice, once by each assessor. The HALO was used first, followed by the UG. Assessor order was randomly assigned. A third research assistant recorded all the measurements.

The assessors then instructed the participant to return to the starting position and the procedure was repeated for each of the remaining AROM shoulder motions: abduction, IR, and ER. The four active shoulder ROM movements were assessed with the participant in supine following the procedures outlined by
Norkin and White,1 specifying anatomic landmarks and accounting for thoracic extension during shoulder flexion in supine (Figures 1a-d). When eligible for bilateral assessment (i.e. no shoulder pathology), this procedure was repeated for the contralateral shoulder as well. All measurements were repeated for each shoulder, with verbal instruction and demonstration without the warm-up step, for a second trial. The warm-up step was not repeated between trial 1 and 2 as this would further increase the number of repeated motions, potentially increasing the change in ROM between trials. Additionally, the participants were already familiarized with the desired active motions by practice through the initial warm up and first trial.

Statistical Analysis
A sample size of 42 was estimated using the method described by Walter et al.15 Statistical analyses were performed using IBM SPSS Version 23 (Armonk, NY: IBM Corp.) Means and standard deviations for continuous data as well as frequencies and percents for categorical variables were calculated for baseline demographic characteristics. Intraclass correlation coefficient and 95% confidence intervals were calculated for inter- and intra-rater reliability and agreement, using a two-way mixed model, with fixed raters, and evaluated absolute agreement. ICC was used to calculate intra-rater reliability between measure one and measure two for each rater. Inter-rater reliability was calculated using the average of the two measures from Rater A and the average of the two measures from Rater B (ICC). In order to quantify variability and measurement error, standard error of measurement (SEM) and smallest real difference (SRD) were calculated. SEM was calculated using the item variance from the ICC analysis of variance output. The square root of the item variance is the SD, and was then used in the formula for calculating the SEM: SEM = SD * \sqrt{(1-ICC)}. The SRD was calculated from the SEM: 1.96 (SEM * \sqrt{2}). The SRD is also known as the minimally detectable change (MDC).

RESULTS
Data were analyzed for 75 shoulders (39 right, 36 left) from 41 participants. Seven participants had only one shoulder evaluated due to past or current shoulder dysfunction or pain. Participants included 30 females and 11 males with an age range of 18 to 70. All but one of the participants were right-handed (Table 1).

Intra-rater reliability ICC, SEM, and SRD values are presented in Table 2. Intra-rater reliability ICCs for the HALO ranged from 0.82 to 0.91, and for the UG 0.83 to 0.95. All ICC values were within the good (>0.75) to excellent (>0.90) reliability ranges for both devices. SEM and SRD values were similar between devices and raters for flexion ROM, as was the case for internal and external rotation. However, the SEM and SRD values for the HALO were higher compared to the UG in all positions, with the exception of flexion for Rater B, which revealed...
a higher value for the UG compared to the HALO device. SEM and SRD values were highest for abduction ROM measured with the HALO, particularly for Rater A. The intrarater SRD for the HALO was 6.9 to 21.1 degrees, and 6.8 to 15.1 degrees for the UG, depending on the motion.

Inter-rater reliability ICC, SEM and SRD values calculated are presented in Table 3. Inter-rater reliability ICCs for the HALO ranged 0.89 to 0.98, which is considered good to excellent. For the UG inter-rater reliability for ICCs ranged from 0.90 to 0.98, all of which are considered excellent. The SEM and SRD values for the HALO revealed higher numbers compared to the UG for flexion and abduction but were essentially the same for IR and ER. The inter-rater SRD for the HALO was 4.9 to 13 degrees, and 4.6 to 7.4 degrees for the UG, depending on the motion.

To determine the accuracy of the digital goniometer, the ICCs for agreement, comparing the HALO digital goniometer to the UG, are presented in Table 4. ICCs ranged from 0.79 to 0.99. The highest ICC values were calculated for IR and ER, followed by abduction, then the lowest values for flexion. However, all ICC values for validity between the instruments were considered good for flexion and excellent for the other three motions.

## DISCUSSION

This is the first study to compare the HALO device to the UG for assessment of shoulder AROM. The results of this study provide clinically relevant information regarding the use of the HALO digital goniometer by physical therapists to measure complex shoulder AROM. The initial aim was to determine reliability of the HALO and validity of the HALO compared to the UG. An ICC for reliability of >0.75 is considered good and >0.90 is considered excellent. All intra-rater reliability ICCs are between 0.82 and 0.91 for the HALO, and 0.83 to 0.95 for the

---

**Table 1. Demographics (n = 41 participants*).**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>32.30 (2.12)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22.63 (2.29)</td>
</tr>
<tr>
<td>Dominant upper limb</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>40 (97.6%)</td>
</tr>
<tr>
<td>Left</td>
<td>1 (2.4%)</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>11 (26.8%)</td>
</tr>
<tr>
<td>Females</td>
<td>30 (73.2%)</td>
</tr>
<tr>
<td>Sides evaluated (n=75 shoulders)</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>39 (52%)</td>
</tr>
<tr>
<td>Left</td>
<td>36 (48%)</td>
</tr>
</tbody>
</table>

BMI: Body mass index (kilograms per meter squared), SD: Standard Deviation

*of 41 participants 34 had bilateral shoulder assessments

---

**Table 2. Intra-rater reliability for shoulder range of motion.**

<table>
<thead>
<tr>
<th>Movement (Rater)</th>
<th>Halo ICC&lt;sub&gt;3,1&lt;/sub&gt; (95% CI)</th>
<th>Halo SEM</th>
<th>Halo SRD</th>
<th>Goniometer ICC&lt;sub&gt;3,1&lt;/sub&gt; (95% CI)</th>
<th>Goniometer SEM</th>
<th>Goniometer SRD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion (Rater A)</td>
<td>.86 (.77-.91)</td>
<td>2.7</td>
<td>7.5</td>
<td>.83 (.71-.90)</td>
<td>2.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Flexion (Rater B)</td>
<td>.88 (.79-.92)</td>
<td>2.5</td>
<td>6.9</td>
<td>.84 (.75-.90)</td>
<td>2.8</td>
<td>7.7</td>
</tr>
<tr>
<td>Abduction (Rater A)</td>
<td>.86 (.77-.91)</td>
<td>7.6</td>
<td>21.1</td>
<td>.94 (.90-.96)</td>
<td>3.9</td>
<td>10.8</td>
</tr>
<tr>
<td>Abduction (Rater B)</td>
<td>.91 (.85-.94)</td>
<td>5.1</td>
<td>14.1</td>
<td>.95 (.92-.97)</td>
<td>3.5</td>
<td>9.8</td>
</tr>
<tr>
<td>IR (Rater A)</td>
<td>.82 (.71-.89)</td>
<td>5.7</td>
<td>15.9</td>
<td>.83 (.73-.89)</td>
<td>5.5</td>
<td>15.1</td>
</tr>
<tr>
<td>IR (Rater B)</td>
<td>.85 (.75-.90)</td>
<td>5.7</td>
<td>15.9</td>
<td>.87 (.78-.92)</td>
<td>5.2</td>
<td>14.3</td>
</tr>
<tr>
<td>ER (Rater A)</td>
<td>.90 (.84-.94)</td>
<td>4.2</td>
<td>11.7</td>
<td>.90 (.85-.94)</td>
<td>4.0</td>
<td>11.1</td>
</tr>
<tr>
<td>ER (Rater B)</td>
<td>.89 (.82-.93)</td>
<td>4.3</td>
<td>11.9</td>
<td>.88 (.81-.92)</td>
<td>4.2</td>
<td>11.7</td>
</tr>
</tbody>
</table>

CI: Confidence interval; ER: External Rotation; ICC: Intraclass correlation coefficient; IR: Internal Rotation; SEM: Standard Error of the Measurement; SRD: Smallest Real Difference
UG. Thus, both are considered good to excellent for all AROM measurements performed in this study, providing evidence for the use of either the HALO device or the UG for measurement of shoulder AROM. These findings are consistent with previous studies that evaluated standard goniometry\textsuperscript{5,7,8} and the HALO.\textsuperscript{14} Similarly, the inter-rater reliability for the HALO was considered good to excellent (0.89 to 0.98) and for the UG considered excellent (0.90 to 0.98). The two raters in this study demonstrated consistent, reproducible measurements between their individual measurements, and between one another for both the HALO and for the UG for all shoulder motions.

Overall, the ICCs for intra-rater reliability for both the HALO and the UG tended to be slightly lower than those for inter-rater reliability. This finding may be due to the fact that subjects went through the motion a second time for the second measurement, and it is possible that the subjects gained motion with the third movement despite performing an initial, pre-measurement, warm-up motion. Additionally, subjects held the motion at end range for a period of time for two raters to measure with each instrument, which may have resulted in a true change in ROM.

The ICCs for accuracy, comparing the HALO digital goniometer to the UG, all fell in the good to excellent range (0.79 to 0.99). The lowest ICC was found for flexion (0.82 and 0.79 for Rater A and Rater B, respectively), which may be due to difficulty visualizing the mid-axillary line and the joint axis during movement. Because ICCs are considered excellent for abduction, internal rotation, and external rotation, the HALO digital goniometer appears to be a valid tool for measuring these shoulder motions, compared to the reference standard of the UG; however, because agreement was lower in flexion,
additional evaluation of its accuracy, with emphasis on using standardized protocols and device placement, is warranted, particularly for this movement. Also, the two devices should not be used interchangeably to evaluate a single individual’s change over time for any motion.

The SRD, the smallest real difference, also known as the minimal detectable change, represents the amount of change in a patient’s ROM beyond measurement error. The intrarater SRD for the HALO was 6.9 to 21.1 degrees, and 6.8 to 15.1 degrees for the UG, depending on the motion. SRD was highest for abduction measured with the HALO (14.1 degrees for Rater B and 21.1 degrees for Rater A). Higher intra-rater SRD values were seen for Rater A for flexion and abduction compared to Rater B, and for both raters SRDs were greatest for abduction, followed by IR. The variability associated with these measurements could be explained by difficulty in consistently identifying bony landmarks for reference or variability in maintaining the plane of motion. That the SRD is greatest for the HALO when measuring abduction suggests that more training may be required to reduce variability and error when using this device.

Despite the strengths of this study, there are limitations that warrant consideration. A particular challenge during this study was the need to repeat abduction measurements due to device “error”, as the display would produce error whenever the user tilted the device out of the horizontal plane. After consulting with the manufacturer to review technique and to identify the issue, it was determined that when the device is moved out of the horizontal plane, the altered position of the accelerometer intermittently created marked measurement errors, necessitating repeated measurement. These obvious instrument errors were well over 90 degrees and obviously not related to rater measurement error. Thus, these measurements were repeated and the erroneous data were excluded from data analyses. The HALO device is sensitive to changes out of the plane of movement and greater skill and more practice may be needed for greatest accuracy, relative to the UG. Additionally, participant safety should be carefully considered during shoulder abduction measurements due to the direction of the laser pointing toward the participant’s eyes. This risk was minimized by instructing the participant to close their eyes during measurement. Fortunately, the type of laser used in the HALO device is low level and does not cause harm with limited exposure (per manufacturer report).

Third year physical therapy students measured AROM on a convenience sample of participants with healthy shoulders only, therefore, study findings cannot be generalized to the clinical setting of therapists with significantly more years of experience, nor to patients with shoulder impairment, nor to other joints. Additionally, while the results of this study provide support for the reliability and validity of this tool, the time required (as a proxy for efficiency) for ROM measurement was not tracked in this study. It was decided to not to evaluate time required in the context of this study due to the need for blinding and repeated measurement. The time necessary to train therapists how to properly use the HALO may be a significant consideration. Finally, the experience of the investigators in this study suggests that this device is challenging to use for assessment of horizontal motions (i.e. for assessment of abduction in the anatomic coronal plane, but measured in supine). This issue is not an issue for the UG because it is not sensitive to tilt out of any cardinal plane. The manufacturer provides alternative methods for measurement of joint angles that may improve ease of use but these must also be assessed for reliability and accuracy. Additional diagnostic studies are needed to determine the most reliable and accurate landmarks and procedures for use of the HALO, so that standardized protocols can be developed for research and for clinical practice.

CONCLUSIONS
The results of this study suggest that the HALO laser guided digital goniometer may be a viable alternative goniometric device for healthcare practitioners to measure active shoulder range of motion. The UG demonstrated lower SRDs for all measurements except for shoulder flexion intra-rater reliability, which suggests that the use of the less expensive UG may provide less measurement error than the HALO device for measurement of AROM of the shoulder. However, the HALO may provide advantages over
the UG for some clinicians: 1) the ability to use only one hand during measurements, which could be helpful for clinicians with disabilities of the upper extremity, and 2) an easy-to-read digital display with memory features, which may be of benefit for therapists with visual impairments. Further research must be done to investigate the reliability and validity of this device in patients with shoulder impairments, as well as its accuracy in measuring ROM of other joints.

REFERENCES
ABSTRACT

Background and Purpose: The nervous system plays a significant role in groin/hip flexor pain which is a common complaint in the active population. Patient examinations that lack consideration of the nervous system’s involvement may result in chronic pain and dysfunctional breathing patterns due to continuously excited (also known as “up-related”) primal reflexes. Primal Reflex Release Technique™ (PRRT™) is a novel treatment paradigm that was designed to calm primal reflexes from their excitatory state. The purpose of this case series was to describe the effects of down-regulating primal reflexes using PRRT™ on pain, function, and breathing pattern dysfunction in subjects who presented with groin and hip flexor pain and exhibited hyperesthesia to TriggerRegions™ in areas of respiration.

Case Descriptions: Six subjects with acute groin and/or hip flexor pain were examined using a battery of tests including muscle integrity strength and range-of-motion (ROM) measurements, special orthopedic tests, breathing functionality and PRRT™ rib palpation assessments. If subjects were determined to be potential PRRT™ responders through PRRT™ rib palpation assessments, the technique was performed according to PRRT™ guidelines. Outcome measures including the Numeric Pain Rating Scale (NPRS), Patient Specific Functional Scale (PSFS), the Global Rating of Change (GRoC) Scale, and the Disability in the Physically Active (DPA) Scale were collected to determine the effects of the treatment.

Outcomes: All subjects demonstrated full resolution of pain as reported on the Numeric Pain Rating Scale, and the change was statistically (p = 0.001) and clinically significant. All subjects returned to optimal function as reported on the Patient Specific Functional Scale, and the change was both clinically (minimal detectable change) and statistically significant (p = 0.001). All subjects returned to normal breathing function as observed through the seated assessment of lateral expansion test. The number of treatments (mean = 1.83 ± 1.16) and time to the resolution of symptoms was minimal (mean = 2.833 ± 2.56 days).

Discussion: By assessing and treating abnormal breathing patterns, postulated to be a result of a sustained excitatory nervous system, subjects returned to full activity, without pain, in less than three days. After a two-week follow-up, subjects remained functionally pain free. Considering the state of the nervous system in the presentation of musculoskeletal pain and not focusing all treatment on local muscle structures may be beneficial. A multifaceted assessment approach is needed to determine other pain factors.

Level of Evidence: Level 4

Key Words: Adductor pain, Breathing Assessment, Primal Reflexes

CORRESPONDING AUTHOR

Valerie F. Stevenson, DAT, ATC, CSCS
Associate Head Athletic Trainer
Texas Woman’s University
500 South Interstate 35E Apt 936
Denton, TX 76205
Office: 940-898-2376
E-mail: Valerie.stevenson12@gmail.com

1 Texas Woman’s University, Denton, TX, USA
2 University of Idaho, Moscow, ID, USA

Conflict of Interest Statement: The authors do not have any conflict of interest, financial or otherwise, to report pertaining to the study.
INTRODUCTION/BACKGROUND
Groin and hip flexor injuries often result in significant time lost from athletic activity,\(^1\) which is likely partially due to the difficult differential diagnostic procedure associated with this presentation.\(^2\) Diagnostic difficulty arises due to patients complaining of general groin pain who may have experienced a variety of mechanisms of injury and presentations including direct musculoskeletal pain and dysfunction or indirect referred pain pathologies, such as gynecological dysfunction, appendicitis, or sports hernia.\(^3,4\) Referred pain to the groin area most likely is due to anatomical course of the genitofemoral nerve through the psoas major, a strong hip flexor.\(^5\) Common mechanisms of injury include resisted hip flexion or passive hip hyperextension, usually caused by running, sprinting, or participating in change-of-direction activities.\(^6,7\)

Sprinting during athletic activities is demanding on both the musculoskeletal and respiratory systems.\(^8\) Rapid movement of the diaphragm during inhalation and exhalation results in an excess of carbon dioxide (CO\(_2\)) and creates an acidic environment within the muscle tissue.\(^8\) The body may then respond by interpreting this reaction as respiratory distress, which may trigger dysfunctional diaphragmatic movement. Normal breathing patterns require input from the sympathetic nervous system;\(^9\) however, if the body anticipates a threat to normal breathing rhythm, it will activate the brain’s defense reflex system and signal the primal startle response to initiate an increase in sympathetic nervous system involvement.\(^10\) Receiving constant signals from the sympathetic nervous system could impact resolution of symptoms after injury or overuse, because the patient remains in a heightened state of neurological stress.\(^11,12\) Patients with dysfunctional diaphragmatic movement may also report pain in the hip girdle structures in because the psoas major (a primary hip flexor) and quadratus lumborum both run superiorly into the region of the diaphragm via fascial, musculotendious and ligamentous connections.\(^13\)

Determining the correct diagnosis of the primary structures involved in groin and hip flexor pain is critical to the selection of the most appropriate intervention and to the reduction of time lost to injury.\(^1,14\) Because of the possibility of multifaceted origins of groin and hip flexor pain, a multidisciplinary approach to treatment is needed if effective and positive outcomes are to be achieved. Such an approach involves musculoskeletal, neurological, and diaphragm dysfunction assessments. If the state of the nervous system is not assessed and treated (perhaps through calming excited reflexes), local interventions and rehabilitation directed at the hip region can be extensive in nature and, ultimately, ineffective.

Traditionally, treatment of a suspected muscle injury would include rest, ice, compression, and elevation (RICE) for the first 24 to 72 hours.\(^1,2,7,13\) As pain decreases and rehabilitation begins, additional methods are used to return the patient to activity. Some treatment protocols, involving both passive movement and active strengthening components, are more effective than others, and many require a significant amount of time and commitment to physical therapy.\(^13\) Passive interventions for groin and hip flexor pain consisting of manual massage, stretching, and modalities have been shown to not be as effective as an active strengthening program; however strengthening programs could take between 8 to 12 weeks to produce effective results.\(^13\) Due to the extensive amount of time needed for an active strengthening program to produce positive results, an investigation into an expedited effective treatment technique for treating groin and hip flexor pain is needed. One novel treatment paradigm that has the potential to treat groin and hip flexor pain is Primal Reflex Release Technique™ (PRRT™).

Primal Reflex Release Technique™ is designed to treat primal reflexes that have been elicited during the startle or withdrawal (nociceptive) response to injury. The paradigm includes a one-minute nociceptive exam that evaluates TriggerRegions™, which are areas of hyperesthesia that are sensitive to the smallest amount of pressure. The clinician bilaterally palpates given areas and determines if the patient responds to touch in any of three ways: a gasp, a groan, or a grimace. Areas that elicit those responses are treated with PRRT™ and are then reassessed for changes in tightness or tenderness, or for thickened appearance. Individual areas are also assessed independently of the 1-minute nociceptive exam and are treated using specialized PRRT™ intervention techniques.\(^15,16\)
The treatment technique involves reflexively and reciprocally inhibiting the aforementioned reflexes that are in a constant state of up regulation and due to injury. The treatment is performed by lightly tapping the facilitated areas' deep tendon reflexes (DTR) for approximately 12 seconds. Tapping these areas stimulates the reflexive properties within the muscle without causing increased pain.15,16

The following case series was based on the premise that primal reflexes elicit protective neuromuscular mechanisms after injury and that dysfunctional breathing patterns can result from reflexive muscle splinting of the muscles of respiration, in turn causing nervous system dysfunction. The purpose of this case series was to describe the effects of down-regulating primal reflexes using PRRT™ on pain, function, and breathing pattern dysfunction in subjects who presented with groin and hip flexor pain and exhibited hyperesthesia to TriggerRegions™ in areas of respiration.

CASE DESCRIPTION
The subjects (n = 6) in this case series were all females whose primary complaint was hip flexor and/or general groin area tightness and pain. The subjects were all otherwise healthy and were physically active in either collegiate or recreational sports at the time of injury. Their ages ranged from 18 to 26 years (mean = 21.33 ± 2.94; Table 1).

CLINICAL IMPRESSION #1
The subjects reported various mechanisms of injury during athletic activity; however, all subjects described a history of pain in her hip/groin area after explosive athletic movements, such as sprinting, jumping, stopping, or changing direction. All injuries were acute in nature and occurred within three days of their initial examination. All subjects were evaluated using an extensive injury history and standard orthopedic examination of the hip (e.g., range of motion (ROM) measurements, strength assessments, special tests for region specific hip musculature involvement); which included Ely's test and Thomas test for muscle length and restriction (Table 1). Subjects were to be excluded from this case series if any of the following was suspected during the initial examination: fractures, hip pointers, acetabulofemoral joint pathology (e.g., labral tear), or complete muscle rupture. Institutional review board (IRB) approval at Texas Woman’s University was given prior to the collection of all patient outcomes, and all subjects gave informed, written consent for sharing the outcomes of their treatments.

EXAMINATION
Initial orthopedic testing resulting in a positive response to either Ely's test or Thomas test indicated subjects could receive local muscular treatments for rectus femoris spasticity or anterior/lateral capsular restrictions; although no local muscular or capsular manual therapy treatments were performed on any of the subjects. Furthering testing also included diaphragm and breathing assessments to determine if nervous system dysfunction or involvement could be the basis of the resulting hip pain.

DIAPHRAGM/BREATHING ASSESSMENTS
Subjects were classified as PRRT™ responders based on rib palpation findings acquired during each
Patient's initial evaluation (Table 2). Rib palpations were performed at intake, each subject's visit, discharge, and at the two-week follow-up. Rib palpations were performed to assess for rib tenderness and movement restriction in three different areas and to determine the appropriate PRRT™ treatment to utilize. The three assessed areas included the first and second ribs (Figure 1), the sixth and seventh ribs (Figure 2), and the eleventh and twelfth ribs (Figure 3). All areas were assessed bilaterally. All six subjects were classified as potential PRRT™ responders because they exhibited rib tenderness involving at least one of the rib palpation locations. Specific palpation locations and directions were determined as instructed in the PRRT™ paradigm.15,16

Rib and abdominal movement during breathing were assessed using the Seated Assessment of Lateral Expansion (SALE), which is similar to the modified Manual Assessment of Respiratory Motion (MARM) test.17 The SALE was performed at intake, each subject's visit, discharge, and the two-week follow-up. The SALE was performed with the patient seated comfortably on a plinth, with knees in flexion and hanging from the plinth (Figure 4). The clinician sat behind the patient and placed her hands on the lower lateral rib cage, bilaterally (Figure 5). The patient was instructed to breathe normally, and an assessment of the overall vertical motion relative to the overall lateral motion was recorded as “lateral motion,” “vertical motion,” or “balanced motion.”18

<table>
<thead>
<tr>
<th>Patient</th>
<th>1st treatment</th>
<th>2nd treatment</th>
<th>3rd treatment</th>
<th>4th treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 1. Finger placement for 1st and 2st rib palpation.

Figure 2. Finger placement for 6th and 7th rib palpation.

Table 2. Total number of 3 sets of 3 repetitions performed during first through fourth treatments.
OUTCOMES SCALES

To assess the effect of the treatment, the following patient outcome scales were collected: The valid and reliable cumulative verbal Numeric Pain Rating Scale (NPRS) was used to assess the pain level at the current time, the best pain level in the past 24 hours, and the worst pain level in the past 24 hours. The NPRS is an 11-point scale (0-10), where 0 equaled “no pain” and 10 equaled “extreme pain.” Current NPRS and the Global Rating of Change (GRoC) Scale scores were taken at the end of each treatment session. The GRoC scale that was used in this case was a 15-point patient-reported perception scale that quantified the extent of improvement or regression experienced by the patient as a result of treatment. The scale begins with -7 (“a very great deal worse”) and ends with 7 (“a very great deal better”).

The valid and reliable Patient Specific Functional Scale (PSFS) was taken to assess the subjects’ level of functional activity. Using an 11-point scale (0-10), each patient rated one formerly-functional activity that had become dysfunctional due to injury. A score of 0 represented the patient’s inability to perform the activity; a score of 10 represented a full return to functional activity. The NPRS, PSFS, and GRoC were collected at intake, daily, and at discharge; the GRoC collected at intake was collected immediately after the first treatment intervention.

The valid and reliable Disability in the Physically Active (DPA) scale was taken to assess patient
impairment, functional limitation, disability, and health-related quality of life.\(^{25}\) The DPA Scale is a questionnaire in which responses are based on a scale ranging from 1 (no problem) to 5 (severe problem) across 16 items; 16 points are subtracted from the total to create a total possible score range from 0 to 64 points.\(^{25}\) A normal, healthy range has been observed to be a score of less than 35.\(^{25}\) The DPA scale was collected at intake and discharge, only. All outcome measures were repeated at a two-week follow-up, although only four of the six subjects were able to follow up at two weeks post discharge.

**CLINICAL IMPRESSION #2**

After assessing for dysfunctional breathing patterns and hyper-sensitivity of rib palpations, subjects were classified as possible PRRT™ responders and treated using the indicated methods of the technique. Initial improvements in patient outcome measures taken both pre- and post-treatment determined that the intervention was indicated for all the subjects’ primary complaint, thus the intervention was used until the subject was successfully discharged (Table 1 and Table 3).

**INTERVENTION**

All subjects were treated individually in a single clinician’s athletic training clinic. All rib palpations and treatment sessions were performed with the patient in a supine position. If the patient exhibited first and second rib tenderness, or if the clinician felt any resistance to palpation within the rib space, the patient was instructed to laterally rotate the head to the involved tender side as far as was comfortable and extend the arms straight, so the fingers pointed toward the toes (Figure 6). Next, the patient performed an active side-bend to the side where the tenderness was noted (e.g., right side tender: turn head to the right and side bend to the right), reached down as far as was possible toward the knee while forcefully coughing with each side bend (Figure 7). Each patient performed three sets of three side-bend/cough repetitions before being reassessed for first and second rib tenderness. If tenderness was

<p>| Table 3. Discharge Outcomes Scores/Special Tests. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Patient</th>
<th>DPA</th>
<th>NRS</th>
<th>PSFS</th>
<th>GRC*</th>
<th>Ely’s Test</th>
<th>Thomas Test</th>
<th>Tenderness</th>
<th>SALE</th>
<th>Total # of days from intake to discharge</th>
<th>#Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>1</td>
<td>9</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>Balanced</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>0</td>
<td>10</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>Balanced</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>0</td>
<td>9</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>Balanced</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>0</td>
<td>9</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>Balanced</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>0</td>
<td>9</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>Balanced</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>1</td>
<td>10</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>Balanced</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

*Overall from intake to discharge
DPA: Disability in the Physically Active scale, NRS: Numeric Pain Rating Scale, PSFS: Patient Specific Functional Scale, GRC: Global Rating of Change Scale
SALE: Seated Assessment of Lateral Expansion.
reported or resistance was observed, the patient performed three additional sets of three side-bend/cough repetitions and was then reassessed.

If the patient exhibited sixth and seventh rib palpation tenderness on either the right or left side associated with the costo-sternal region, she was instructed to lie in a supine position and flex the arm on the involved side to approximately 100°. The patient was then told to abduct approximately 10° from that position (Figure 8). The clinician stood at the involved side and placed a hand on the wrist of the flexed and abducted arm. The clinician then instructed the patient to pull toward the opposite hip in a diagonal fashion (e.g., across the chest) while the clinician resisted the motion (Figure 8). The clinician’s isometric resistance was provided for five seconds and was then released. The resistance was strong enough that when it was released, the patient was not able to control or stop the horizontal movement to the opposite hip (Figure 9). The horizontal arm pull was performed for three sets of three repetitions, and then the sixth and seventh ribs were reassessed for tenderness and movement restriction. If tenderness was reported or movement restriction of the ribs was present, three additional sets of three pulls were performed, and the patient was reassessed again.

If the patient exhibited eleventh and twelfth rib tenderness associated with the PRRT™ diaphragm-specific reflex release assessment, she was then instructed to turn her head to the uninvolved side and then side bend to the involved side while coughing (e.g., right side tender: turn head to the left and side bend to the right) (Figure 10). The patient was asked to perform three sets of three repetitions, after which the eleventh and twelfth ribs were reassessed for tenderness and movement restriction. If tenderness was noted, three additional sets of three repetitions were performed.

All treatment interventions were applied in groups of three sets of three repetitions until rib tenderness and/or movement restriction was resolved, at which point the current NPRS for groin and hip flexor pain
and the PSFS were taken. The number of sets performed by each patient varied during each treatment session: The first session required the most sets (3 ± .894), with Subject 6 requiring the maximum number of four sets, and Subject 3 needing the minimum number of two sets. If a subject needed additional treatment sessions, 2.33 ± .577 sets were needed for the second treatment session, while the third and fourth treatment session required three and one set, respectively (Table 2).

DATA ANALYSIS
To evaluate a change in pain and functional scores over time, a one-way repeated measures analysis of variance (ANOVA) was performed using SPSS (SPSS version 23.0; SPSS Inc., Chicago, IL, USA). No significant difference (F2,2 = 13.796, Wilk's λ = .068, p = .068, partial η2 = .932, power = .523) in pain was reported over time from intake (mean = 5.65 ± 1.044) to discharge (mean = .500 ± .289) to the two-week follow-up (mean = 0). However, the large effect size implied by partial η2 indicates that over 90% of the positive variability, or improvement in pain, may be attributed to the PRRT™ treatment intervention. Further, Cohen's d effect size calculations (d = 6.723) indicated a large magnitude of effect of PRRT™ on pain, with less than 20% of the follow-up scores coinciding with pain scores taken at intake. Although a statistically significant difference was not found in the initial ANOVA, post hoc comparisons were conducted because of the exploratory nature of this study and the risk of a Type II error due to the observed low power (.523); thus, further statistical comparisons were needed to assess any other potential differences across time. Pairwise comparisons revealed a significant difference (mean difference = 5.15 ± .850, p = .027, 95% CI: 1.022, 9.278) between intake and discharge scores, as well as a significant difference between intake and the two-week follow-up (mean difference = 5.65 ± 1.044, p = .037, 95% CI: .581, 10.719), scores. Moreover, the mean differences between intake and discharge and intake and the two-week follow-up both exceeded the NPRS minimal clinically significant difference (MCID), and were, therefore, clinically significant.

No difference was noted from discharge to follow-up (mean difference = .500 ± .289, p = .545, 95% CI: -.902, 1.902), which indicates that subjects remained within the same level of pain that they achieved at discharge and did not have a return in symptoms.

A one-way repeated analysis of variance (ANOVA) was conducted to determine a change in functional scores over time. For the PSFS, a significant difference (F1, 3 = 121.000, Wilk's λ = .024, p = .002, partial η2 = .976, power = 1) was reported over time

<table>
<thead>
<tr>
<th>Table 4. Two-week Follow-up Outcome Scores/Special Tests.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

*Overall from intake to 2-week follow up
DPA: Disability in the Physically Active scale, NRS: Numeric Pain Rating Scale, PSFS: Patient Specific Functional Scale, GRC: Global Rating of Change scale, SALE: Seated Assessment of Lateral Extension
from intake (mean = 6.500 ± .577) to discharge (mean = 9.500 ± .577) to the two-week follow-up (mean = 9.250 ± .500). Mean differences in scores between intake and discharge and between intake and follow-up exceeded the MDC24 for the PSFS, which added clinical meaning to the statistical differences observed in outcomes scores.

A repeated measures ANOVA was also performed to assess for differences in scores measuring patient impairment, functional limitation, disability, and health-related quality of life as indicated by the DPA Scale. No significant difference (F2,2 = 9.332, Wilk's λ = .097, p = .097, partial η2 = .903, power = .404) was found for subjects' DPA Scale scores. Post hoc comparisons were conducted and pairwise comparisons revealed significant differences between intake and discharge scores (mean difference = 8.250 ± 1.652, p = .046, 95% CI: .227, 16.273) and between intake scores and follow-up scores (mean difference = 7.250 ± 1.377, p = .040, 95% CI: .563, 13.937). No difference (mean difference = -1.000 ± .707, p = .757, 95% CI: -4.434, 2.434) was observed between discharge scores and follow-up scores. Additionally, all subjects were discharged within the normal, healthy ranges of a score that is less than 23 for the DPA scale.25

The patient-reported perception of the extent of improvement after PRRT™ treatment, which was measured by the GRoC, also suggests effective treatment as mean scores after the first treatment application (5.00 ± 2.097) to discharge (6.66 ± .516) to the two-week follow-up (7 ± .000) increased. After the first treatment application, most GRoC scores (67%) were reported as “quite a bit better”, which is equal to +5 on the scale, or higher. Additionally, at the two-week follow-up, all of the subjects reported a GRoC score (+7) coinciding with “a very great deal better”, which suggest the subjects perceived a large level of improvement over the course of treatment.

**DISCUSSION**

In this case series, the positive patient outcomes from using PRRT™ may have occurred because the treatment is aimed at treating nervous system dysfunction.15, 16 The reported ineffective and extensive treatments of groin and hip flexor injuries14,27 could be the result of failure to reset (or down-regulate) reflexes that remain in a constant state of excitement (or up-regulation) after injury. Not assessing and addressing nervous system involvement could lead to chronic groin and hip flexor pain, and, due to movement compensations developed because of pain, may place the patient at risk for further injury to the hip girdle musculature. In chronic groin pain cases, symptoms are often complex and uncharacteristically more varied than that of other muscle injuries in other parts of the body.28 After sustaining injury to the groin area, patients have reported areas of pain migrating, over time, to the medial thigh and rectus abdominis.28 Pain signals referred to those areas could be the result of an active nociceptive reflex contributing to central sensitization, and not necessarily the result of soft tissue damage.

An increased response to various stimuli, such as mechanical pressure, chemical substances, light, sound, cold, heat, and electricity, are all outcomes of the processes involved in central sensitization;29 thus, patients' sensitivity to rib palpation during the PRRT™ evaluation could indicate a presence of an over-reactive central nervous system. In addition, assessment of breathing function could also offer insight into the cause of referred groin and hip flexor pain, because sympathetic nerve outflow to skeletal muscles varies during normal respiratory cycles. Sympathetic output decreases during inspiration and then rises to its peak during the end stage of expiration;12 thus, a disruption in normal breathing patterns would affect the normal influence of the nervous system and could render it dysfunctional.30 The common mechanism of injury for all subjects in this case series involved running or sprinting at their maximum speed, which can cause labored breathing that affects diaphragm movement. The results of the SALE determined that all subjects presented with dysfunctional breathing patterns during the initial examination, which could offer support for nervous system dysfunction postulated through abnormal breathing patterns.

By assessing and addressing the nervous system through primal reflex examination and by correcting breathing patterns, subjects in this case series returned to pain-free functional movement. The physiology behind a true muscle tear or strain was not present in these cases; although the subjects
presented with pain and dysfunction in the hip flexor/groin area. Had an actual tear occurred, resetting the nervous system through diaphragm regulation would not have resulted in tissue healing over such a short period of time. No other treatments were performed on these subjects during the active treatment period, nor were any performed during the two-week follow-up period. All subjects participated in full activities during the treatment time period and were not limited in any activities of daily living or sport-related activities.

Several limitations were present within this case series. The clinician administering the treatment was a novice in the uses of PRRT™ and was trained through an introductory home study course. Currently, six levels of PRRT™ are available and offer more advanced techniques as the levels increase. Moreover, the clinician only treated the diaphragm based on rib palpations when other evaluations and treatments within the paradigm may have led to improved results. Other limitations involve the homogeneous nature and size of the sample. All subjects in the study were female, active, and younger than 25 years of age. The results are not generalizable, to all subjects of varied ages, activity level, and of the male sex. Future research could include assessing subjects using the PRRT™ one-minute nociceptive exam and treating all areas in excitatory stress to observe if less time is needed to reach functional pain free activity in subjects presenting with hip flexor or groin area pain. Further research could also include a larger and more diverse sample size.

CONCLUSION

By assessing and treating using Primal Reflex Release Technique™, all subjects in this case series experienced a complete resolution of pain and returned to optimal functional activity without the use of traditional therapeutic exercise or local treatment to hip muscles. Breathing also returned to functional status by the end of treatment, and the subjects remained pain-free and functional up to two weeks after discharge, with no further intervention or activity restrictions.

REFERENCES


ABSTRACT

**Background and purpose:** Elbow pain is common in young gymnasts and is frequently encountered by physical therapists working in direct access outpatient clinics. Most elbow pain is benign; however, non-specific symptoms can mask serious medical pathologies, as is the case with osteochondritis dissecans (OCD). OCD is a joint condition in which bone underneath the cartilage of a joint dies due to lack of blood flow. Risk factor analysis, palpable joint tenderness and swelling, joint locking, and a history of high intensity repetitive activities may inform the clinical reasoning; however, the diagnosis of OCD is best made using magnetic resonance imaging (MRI). The purpose of this case report is to describe the main components of the history and physical examination that led to OCD differential diagnosis.

**Case description:** A 12-year-old female gymnast presented to an outpatient physical therapy clinic with right elbow pain following a compressive trauma. The decision was made to refer the patient for diagnostic imaging evaluation due to localized joint swelling and point tenderness over the radial head, elbow pain with compressive loading, the presence of demographic risk factors, and a recent worsening in her symptoms after a second trauma. MRI subsequently revealed OCD associated with external humeral condyle bone marrow edema. The patient underwent surgical repair.

**Outcomes:** The follow-up MRI at five months post-surgically reported a “excellent graft integration”. A post-operative progressive load management program was initiated, with full return to sport achieved at 10 months after surgery.

**Discussion:** This case report highlights the central role of primary care clinicians, such as physical therapists, in identifying patients with suspected pathologic conditions that may need referral for imaging, medical assessment, or surgical intervention. Physical therapists working in direct access environments should be aware of subtle signs/symptoms and specific risk factors that may be indicative of serious pathologies.

**Level of evidence:** Level 4

**Key words:** Adolescent gymnast, Differential diagnosis, Direct access, Elbow pain, osteochondritis dissecans, Physical therapy
BACKGROUND AND PURPOSE

Elbow pain is a common morbidity among adolescent athletes such as throwers and gymnasts.

The incidence of elbow pain may be as high as 45% in baseball players between the ages of 13 and 14.1 Generally, elbow pain during adolescence has a good prognosis; however, pain can be caused by serious conditions, as osteochondritis dissecans (OCD), requiring specialist care. It is important that physical therapists working in a direct access setting be able to identify those patients who may present with OCD.

The term OCD was used for the first time in 1888 by Koing.2 OCD refers to an acquired lesion of the subchondral bone associated with potential involvement of the overlying cartilage. OCD lesions are most common in the knee, followed by the ankle and elbow,3 with various degrees of fragmentation and sclerosis.2 In OCD lesions of the elbow, the capitellum of the humerus is typically affected. Notably, the incidence of this pathoanatomical lesion appears to be increasing rapidly.4,5 OCD lesions of the elbow can also be found in the radial head, olecranon, and trochlea.

OCD of the elbow is most common in adolescent athletes engaged in upper extremity weight-bearing and repetitive overhead or elbow extension activities—i.e. baseball, tennis, volleyball, weight lifting and gymnastics.6,7 Kida et al., found a prevalence of 3.4% of capitellar OCD lesions in 2,433 adolescent baseball players between 12 and 18 years old. Moreover, it was found that players who started competition at younger ages and played for a longer period showed an increased risk of developing capitellar OCD lesions.8

Interestingly, this condition may be asymptomatic.8 Patients with OCD are usually in their second decade of life, from 11 to 23 years old. Males are more commonly affected than females and dominant elbow capitellum is mostly typically affected.9 However, up to 20% of the patients may develop a bilateral condition.9 The etiology of this disorder is still unclear, but repetitive trauma, vascular, inflammatory, and genetic factors seem to play a role.10 In studies of identical twins, a correlation between OCD lesions and repetitive joint loading sport activities was identified.10 Furthermore, repetitive overhead throwing and loading activities generate considerable compressive forces on the radio-capitellar joint.6,11,12,13 The repetitive forces and trauma exerted on immature articular cartilage of the elbow seem to play a primary role on the etiopathogenesis.14,15 Anatomically the radio-capitellar joint is also susceptible to OCD due to the poor blood supply to the capitellum, characterized by a focal avascular zone (Figure 1), that seems to put individuals at risk for OCD lesions in this articulation.

Typically, the clinical picture in adolescent male athletes includes: elbow pain, radiocapitellar joint tenderness, and swelling over the lateral aspect of the elbow.16 Physical examination findings in the early stage of OCD are non-specific, but early diagnosis is important to prevent the expansion of the lesion and the possible degeneration of the joint, especially in adolescents. Individuals that continue to play sports despite elbow pain tend to develop higher grade osteochondral lesions in the longer term.17

Figure 1. Focal avascular zone of the Radial Capitellum.
Rest and nonsteroidal anti-inflammatory drugs (NSAIDs) reduce the symptoms in the early stages of OCD; however, since acute ligament or muscular sprains/strains will also respond to this intervention, it can lead to a delay in making the correct diagnosis. Generally, patients with capitellar OCD present with a progressive worsening of the activity-related pain and stiffness. In the presence of loose bodies within the joint, loss of active elbow extension (i.e. 15–30°) range of motion and intermittent catching and locking of the elbow tend to occur. Patients with radiocapitellar OCD may also present with articular crepitus, especially with pronation and supination movements; active pronation and supination with the elbow in extension also tends to reproduce familiar pain at the radiocapitellar joint. In a study of 69 adolescents with elbow OCD, Mihara et al. found that the most frequent symptoms are: (1) discomfort or soreness in the elbow during or after throwing (98%), (2) followed by decreased performance (58%), (3) local tenderness (43%), and (4) swelling (18%). None of the 69 patients in this study experienced locking of the elbow joint.

Diagnostic imaging for elbow OCD typically begins with anterior-posterior and lateral plain film radiographs. Sixty-six percent of the patients with known capitellar OCD show pathoanatomical lesions on imaging. Therefore, additional investigation with other diagnostic imaging is usually needed with suspected OCD. Magnetic resonance imaging (MRI) is the gold standard in detecting and evaluating OCD lesions and is able to allow identification of early-stage lesions when plain film radiographs are negative. Furthermore, MRI is helpful in determining the acuity of the condition due to its capacity to detect subchondral edema. CT scans are highly sensitive and may be warranted for the detection of suspected loose bodies within the joint. Various classifications based on radiography, MRI, or arthroscopy have been used to describe OCD lesions. Other types of classifications divide lesions into “early-stage” or “advanced-stage” and into “stable” or “unstable”. Stable lesions are characterized by an immature capitellum with an open growth plate and flattening or radiolucency of the subchondral bone in a patient with normal elbow motion. Unstable lesions have at least one of the following findings: a capitellum with a closed growth plate, fragmentation or at least 20 degrees of elbow motion restriction. Generally, stable lesions may be reversible and can heal completely with conservative management (i.e. rest, splinting or bracing for immobilization), while unstable lesions typically require surgical management.

Mihara et al. proposed guidelines for the management of elbow OCD. Generally, Non-operative treatment and repetitive stress cessation is the management of choice. Surgery is recommended for: (1) closed growth plate early-stage lesions; (2) if new bone formation is not observed on radiography within three to six months of conservative management or when the lesion progresses; (3) advanced-stage lesions. Discontinuing heavy elbow exercise and carrying heavy loads (i.e. conservative therapy) for 6 months has been identified as an important positive prognostic factor in the conservative management of OCD. Patients who were compliant with the conservative therapy for stable lesions had an 84.2% healing rate, while those who had similar lesions but were non-compliant with conservative therapy only experienced a 22.7% healing rate.

Elbow pain is very common in young athletes and physical therapists must be able to recognize the clinical picture of those patients in need of imaging, and surgical management. Thus, early diagnosis may prevent the development of higher grade of osteochondral lesions and joint degeneration in the longer term. Therefore, the purpose of this case report is to describe the main components of the history and physical examination that led to OCD differential diagnosis.

CASE DESCRIPTION

Patient History and Systems Review
A 12-year-old female gymnast presented to the clinic complaining a one-month history of right elbow pain, especially with upper extremity loading activities commonly performed during training. The subject describes an initial mechanism of injury producing sharp elbow pain when she landed on her right hand with the elbow extended during an acrobatics
The subject rated her initial pain as an 8 out of 10 on a Numeric Rating Pain Scale (NPRS) (0, no pain; 10, maximal pain) and stated that her elbow gave out as a result of the pain. The subject was initially evaluated by both a general practitioner (GP) physician and an orthopaedic physician and 7-10 days of rest was prescribed in the absence of serious pathology.

After one week, the subject was pain free with ADLs and returned to gymnastic activities although she continued to have pain (NPRS 5/10) with compressive loading of the elbow in extension.

The pain intensity was 5/10 but would increase to 7/10 during the workout when repeatedly performing any load-bearing activities on the upper extremity. However, the pain intensity quickly reduced a few hours after each training session and was progressively improving. After 2 weeks, a second episode of stabbing pain occurred during the landing phase of a spin jump on the affected hand. One week later, as the pain became disabling and the subject sought care from her physical therapist. Notably, the patient didn't stop gymnastics training and her parents did not permit her to take nonsteroidal anti-inflammatory drugs (NSAIDs) or any other pain medications. The patient denied any significant past or current medical problems. She and her family were concerned about the symptoms progressing and having to stop training in her sport as she had been training four to five times per week since she was five years old.

Clinical Impression #1
The patient's history revealed two sport-related elbow traumas and significant risk factors (i.e. high intensity upper extremity weightbearing activities and patient age) that led the physical therapist to suspect a pathologic condition that may have needed referral. Thus, the main objective of physical examination was to exclude any red flags and examine the structural integrity of the elbow joint.

Examination
Physical examination revealed visually and palpatory swelling over the lateral aspect of the right elbow with full flexion/extension active and passive range of motion (ROM) measures bilaterally. Passive pronation/supination, with extended elbow were also normal. Humeral-radial and humeral-ulnar elbow compression was not painful. Palpation revealed tenderness over the postero-lateral aspect of the radial head. There were no side differences in flexion/extension and pronation/supination manual force accepted during strength testing; however, local discomfort was reported during resisted wrist extension. Elbow Valgus and Varus stress tests were negative. Patient's primary pain complaint was reproduced by the injury motion: elbow hyperextension in a weight bearing or loaded position (i.e. body weight on the hand leaning onto the treatment table). In this position, external over pressure on the radiocapitellar joint by the clinician reproduced the subject's chief complaint.

Additionally, the tuning fork test was performed in order to evaluate the bony integrity. The vibrating tuning fork was placed directly and closely to the suspected fracture site (i.e. the radial head and lateral epicondyle) but was negative. Despite the estimated sensitivity ranging from 75% to 100% negative tests are not sufficient to rule out fractures because this test is not sufficiently reliable or accurate in order to rule in or out fractures and should have only limited use in clinical practice.

Clinical Impression #2
Because of the increased reactivity to compressive load to the joint, the delay of the natural tissue healing, the injury mechanism, and the presence of demographic risk factors in the patient's history being consistent with an OCD presentation, it seemed prudent to consider imaging as part of the subject's evaluation. A decision to contact the referring orthopaedic surgeon to discuss the need for additional diagnostic imaging was made.

Diagnostic Imaging
The initial plain film radiography report identified “Small irregularities of the cortical profile of the external humeral condyle, secondary to a minor traumatic detachment” (Figure 2). Based on the radiography findings, the orthopaedic surgeon prescribed an MRI imaging to further evaluate the severity of the lesion. The MRI identified an 11 mm osteochondritis dissecans associated with bone marrow edema on the
external humeral condyle. Discontinuity of bone cortical was noted also. However, the extremity of the lesion appeared homogeneous. Two cystic areas, one anterior (2.5mm) and one medial (1.5mm), were identified. The cartilage surface seemed regular. Thus, the lesion was considered stable” (Figures 3a and 3b).

Based on the MRI results, the decision of a conservative treatment, which included three months of complete rest from loading sports activities, were prescribed by the orthopaedic surgeon. After this time of rest (i.e. three months after the first MRI) a second MRI revealed a progression to an unstable lesion with fragmentation (Figures 4a and 4b).

For a more detailed description of the timeline from injury to diagnosis to management, see the timeline in Figure 5.

INTERVENTION
Due to the presence of an unstable fragment and the absence of new bone genesis, resection of the osteochondral lesion and repair with enriched mesenchymal cell matrix was performed. The osteochondral lesion was resected and repaired using enriched matrix of mesenchymal cells from the iliac crest. The post-surgical protocol consisted of three weeks of immobilization in 90-degree flexion followed by four months of non-loading rehabilitation (Table 1).

OUTCOMES
The follow-up MRI at five months post-surgically reported a “excellent graft integration” (Figure 6a, 6b). Thus, the orthopaedic surgeon advised another twenty days avoiding any loading of the elbow, to be followed by a progressive load management rehabilitation program until full recovery and a return to sport was achieved (Table 1). A final follow-up MRI was performed five months after the last PT visit.

DISCUSSION
Elbow pain is a common complaint in sport. Physical therapists should be able to recognize serious pathologies outside their scope of practice requiring additional evaluation. This case report highlights the central role of primary care clinicians, such as...
The International Journal of Sports Physical Therapy | Volume 13, Number 4 | August 2018 | Page 731

physical therapists, in identifying patients with suspected pathologic conditions that may need referral for imaging, medical assessment or surgical intervention. Risk factors are well known from the current literature for those patients with elbow OCD. Adolescent athletes that exercise in repetitive overhead or upper extremity weight-bearing activities (e.g., baseball, tennis, volleyball, weight lifting and gymnastics) are specifically at risk.4,6,7 Like the subject described in this case report that started training at 6 years-old, the risk of developing OCD lesions increases in those individuals that begin gymnastic training and competitions at a young age.8 Missing OCD diagnosis in younger patients could lead to an increased risk for the development of higher grade of osteochondral lesions and joint degeneration making it similar to the process of avascular necrosis in the longer term.4

The following clinical features of elbow OCD have been described in the literature:

- Local pain in the radiocapitellar joint area;6,12,18
- Inflammatory-like symptoms after sports activities or load;4
- Progressive worsening of pain and stiffness related to load (98% of cases);6,12,17
- Decreased sport performance (58% of cases);19
- Tenderness at the radiocapitellar joint (43% of cases);19
- Local swelling (18% of cases);19
- Active and passive ROM extension loss (15–30°);6,12,18
- Intermittent catching and locking of the elbow joint;32
- Crepitus, especially during pronation supination movements;6,12,18
- Local pain during active pronation and supination in an elbow extension position;6,12,18
- Positive radiocapitellar compression test;6,12,18
- Ulnar collateral insufficiency and radiocapitellar rotatory instability.4

Risk factors and physical examination findings must be carefully assessed and weighed in order to consider possible diagnoses. This case report describes the clinical features (i.e. a history of trauma and the related injury mechanism; an increased reactivity to compressive load to the joint; the delay in symptom reduction; and the appropriate demographic Risk Factors) and the clinical reasoning that should prompt any clinician in a direct access setting to be suspicious of medical pathology in young sport population. That is to consider the many risk factors (i.e. sport loading activities, a history of long time sports activity, etc.), the behaviour and progression of symptoms especially related to the load.

This case fits with the typical challenges associated with such complex disorder. Therefore, provoking patient's symptoms using functional testing should be considered standard practice when basic tests and measures are unremarkable.
Moreover, this case report describes the natural history and the post-surgical management of OCD of the elbow in a female gymnast. That is, early identification and optimal treatment were critical to optimize lesion healing. Early stage attempts at conservative treatment (i.e. resting phase in respect of the repair process) followed by a long-term post-operative program were essential in order to achieve

Figure 5. Timeline of case progression.
<table>
<thead>
<tr>
<th>PHASE</th>
<th>OBJECTIVES</th>
<th>STRATEGIES</th>
<th>EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>Protecting phase</td>
<td>Avoiding any loading of the elbow</td>
<td></td>
</tr>
<tr>
<td>3 weeks - 5 months</td>
<td>Pain management</td>
<td>Pain education, self-management strategies, grade 1-2 mobilization, controlled physiological passive mobilization and soft tissue treatment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range of motion</td>
<td>Grade 3-4 mobilization, passive physiological mobilization into the restriction and Mobilization with Movement. Active Mobilization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muscular activation</td>
<td>Isometric and concentric isonic exercises.</td>
<td>Elbow AROM keeping a ball balanced on the palm or basketball dribbling with a soft sponge ball</td>
</tr>
<tr>
<td></td>
<td>Neuromuscular control</td>
<td>External focus exercises</td>
<td>Biking, Crunch, Bridging, free weight Squatting, etc.</td>
</tr>
<tr>
<td></td>
<td>General strength and conditioning</td>
<td>Aerobic training, core stability and lower limb exercises</td>
<td>Biking, Crunch, Bridging, free weight Squatting, etc.</td>
</tr>
<tr>
<td></td>
<td>Progression of general strength and conditioning</td>
<td>Aerobic training, core stability, legs resistance training and reintroduction upper body exercises with progressive load</td>
<td>Running, superman, plyometric jumping, weight free and elastic resistance on upper extremity exercise (i.e. biceps curl, elbow extension, shoulder press, etc.), etc.</td>
</tr>
<tr>
<td></td>
<td>Muscular strength and endurance</td>
<td>Push and pull exercise with elastic resistance or bodyweights (see the next progression) and grip exercises</td>
<td>Elastic resistance chop, diagonal Elastic resistance superman, wall push-up, etc.</td>
</tr>
<tr>
<td></td>
<td>Joint load capacity</td>
<td>Maintenance of position for 60° at different ROM weight bearing load on upper extremity on stable surfaces, pulling, knee push-up (progression of position: push up, v push up, hand stand, reaching in push-up position), etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stability</td>
<td>Weight bearing load on one upper extremity One arm plank, side plank, push up on unstable surfaces (balls, TRX, rings), handstand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sport Specific Rehabilitation</td>
<td>Dynamic uncontrolled exercise Rings exercises (pull up, dips), handstand walking, Front walkover, back walkover, etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Return to sport</td>
<td>Sport specific exercises: Front handspring, back handspring, etc.</td>
<td></td>
</tr>
</tbody>
</table>
Finally, preparatory and sport-specific exercises were performed until the progressive return to sport, 10 months after surgery.

CONCLUSIONS
To the best of authors’ knowledge this is the first documented case of capitellar OCD recognized by a physical therapist in a direct access setting, resulting in operative management of the condition. The subject achieved full return to sport postoperatively (state time frame). Physical therapists are capable of screening patients in need of medical referral for further examination or investigation of conditions.33-46,47

REFERENCES

Figure 6. (a) After surgery MRI. T1 Coronal view shows an excellent bone graft integration. (b) After surgery MRI. T2 Sagittal view shows the resolution of the lesion with an excellent bone graft integration.

a successful outcome.4,6-7,29 Specifically, in this case the subject had a five-month period of load avoidance in order to protect the graft. After graft integration was documented by the follow-up MRI the subject then underwent a progressive load management program with the goal of restoring the coordination skills, strength, and load capacity necessary for gymnastics participation. Accordingly, a general athletic fitness and conditioning program was introduced as soon as possible during rehabilitation.


ABSTRACT

**Background:** Surgical outcomes following isolated posterior cruciate ligament reconstruction (PCLR) have been noted to be less satisfactory than the anterior cruciate ligament. Limited understanding of optimal rehabilitation has been implicated as a contributing factor.

**Hypothesis/Purpose:** The purpose of this review was to gather the literature related to isolated PCLR rehabilitation, extract and summarize current rehabilitation guidelines, identify timeframes and functional measurements associated with common rehabilitation topics and provide recommendations for future research.

**Study Design:** Literature review.

**Methods:** A literature review was performed for scientific publications that include a detailed rehabilitation program following isolated PCLR, published between January 2005 and March 2018. Data related to weight-bearing, knee range of motion (ROM), brace usage, specific exercise recommendations and suggestions for return to running and sport activities were extracted and categorized.

**Results:** A total of 44 articles met inclusion criteria. Post-operative weight-bearing was discussed in 35 articles with recommendations ranging from no restriction to 12 weeks of limitations. Forty-two articles recommended the use of immediate post-operative bracing, the majority of which positioned the knee in full extension, with duration of use ranging from one to 12 weeks post-operatively. Although 30 articles offered detailed descriptions of ROM activity, there was significant variability in timing of initiation, angular excursion and progression of range of motion. Suggested timeframes for returning to sports activity ranged from four to 12 months, with only four articles providing specific objective strength or functional performance criteria necessary for progression.

**Conclusions:** There is substantial variation in nearly all aspects of published descriptors of rehabilitation following isolated PCLR. Most protocols are based upon biomechanical principles and clinical expertise, relying solely on timeframe from surgery to support rehabilitation decision making. Evidence to compare patient outcomes with specific loading, ROM progression and exercise strategies is currently lacking. Only a small number of protocols incorporate the use of specific objective performance goals to facilitate return to sport decision making.

**Key words:** PCL reconstruction, physical therapy, posterior cruciate ligament, rehabilitation
INTRODUCTION
The posterior cruciate ligament (PCL) functions as the primary restraint against posterior tibial translation at the knee.\textsuperscript{1} PCL injuries typically involve high energy trauma to the anterior proximal tibia, with motor vehicle accidents (dashboard injury) and sports related trauma accounting for the majority of injuries.\textsuperscript{1-3} The incidence of acute PCL injuries has been reported as 1-44% of acute knee injuries, however, isolated PCL tears without additional knee ligament injury are less common.\textsuperscript{4} Several authors have reported good outcomes with conservative (i.e. non-operative) management in cases with grade I or II isolated PCL injuries.\textsuperscript{5} However, surgical management may be indicated for patients with acute grade III PCL injuries, with continued knee pain or instability despite conservative treatment.\textsuperscript{6,7} Although PCL injuries rarely occur in isolation,\textsuperscript{8,9} they occur most often in athletes from a fall on a hyper-flexed knee during sports activity.\textsuperscript{3,10}

Outcomes following PCL reconstruction (PCLR) are inconsistent in terms of restoring normal knee function and kinematics.\textsuperscript{5} This may be related to a lower frequency of PCL surgeries, the complex anatomy of the bundles comprising the PCL, and disagreement on the ideal method of surgical reconstruction technique.\textsuperscript{7,11,12} However, post-operative rehabilitation may also play a fundamental role in outcomes following PCLR.\textsuperscript{13-15} Effective post-operative rehabilitation is essential for optimizing graft healing, obtaining a functionally stable knee, encouraging safe recovery of athletic activity, and minimizing the risk of re-injury.\textsuperscript{13,16} Quadriceps and hamstring strength deficits have been identified at two years post-PCLR which can limit optimal graft protection and sport performance.\textsuperscript{17} There are several aspects of rehabilitation that are commonly discussed in the literature, including the use of early post-operative bracing, weight-bearing status, range of motion (ROM) restrictions, timing of initiation of hamstring exercise, and criteria for return to running and sports activities.\textsuperscript{5,18,19} However, timeframes for implementing these rehabilitation factors are reported with high variability, and there is currently no consensus regarding an optimal rehabilitation program.\textsuperscript{5,18,19}

The first step in addressing these issues is to fully understand the collection of published post-operative PCLR rehabilitation guidelines in the literature. Therefore, the purpose of this review was to gather the literature related to isolated PCLR rehabilitation, extract and summarize current rehabilitation guidelines, identify timeframes and functional measurements associated with common rehabilitation topics and provide recommendations for future research.

METHODS
Search Strategy
A comprehensive search of PubMed, Embase and Cochrane internet databases was performed in order to identify relevant articles. The combination of search terms utilized were “posterior cruciate ligament reconstruction” OR “PCL” AND “rehabilitation” OR “physical therapy”. Due to the evolving strategies for PCL reconstruction surgical techniques and the impact this may have on rehabilitation strategies, this search was limited to articles published from January 2005 to March 2018. All identified references were exported to EndNote reference management software (Version X7; Thompson Reuters Corporation, New York, NY).

STUDY SELECTION
Following removal of duplicate citations, titles and abstracts were screened by two independent reviewers (M.S. and E.G.) for relevance and full-text analysis. Thereafter, full text articles were assessed for eligibility by the same team of reviewers using predetermined eligibility criteria. Eligible articles included information on isolated PCLR only. Studies with multi-ligament or other concomitant surgical procedures were excluded. Selected articles had to specifically outline post-operative rehabilitation guidelines within human subjects and had to be in English language. This literature review is inclusive of studies from Level V to Level I (case reports, case-control designs, cohort studies, prospective studies and randomized controlled trials). Previous literature and systematic review articles were excluded.

ASSESSMENT OF STUDY QUALITY/RISK OF BIAS IN INDIVIDUAL STUDIES
Studies were classified according to Oxford Centre for Evidence Based Medicine (CEBM) Levels of evidence. A formal assessment of risk of bias was not performed as the information extracted for this
review was unrelated to the type of study design or each study's reported results. Thus, for the purposes of this review paper, all extracted data is of equal relevance, irrespective of study quality.

DATA EXTRACTION
Data extraction was performed by M.S. and E.G. and was agreed on by consensus. Any data related to study design, subject characteristics (age, sex), surgical technique including graft choice, details of rehabilitation including weight-bearing status, use of post-operative brace or other immobilization, knee range of motion guidelines, specific strengthening exercise instructions with particular attention to the initiation of hamstring specific strengthening exercises, and criterion for advancement through return to advanced rehabilitation and sports activities was extracted and is outlined in Table 1.

DATA ANALYSIS
Data related to the purpose of this review was tabulated and reported only using frequency distribution.

RESULTS
The search strategy retrieved a total of 378 studies. After screening 54 full-text articles for eligibility, 44 were included in the review. (Figure 1).

STUDY QUALITY/TYPEx
The included studies were classified by level of evidence based on the Oxford Centre for Evidence-based Medicine – Levels of Evidence (I-V). Of the 44 studies, there were 2 level II studies, 10 level III studies, 17 level IV studies and 15 level V studies. There were no studies identified that specifically evaluated differences between rehabilitation techniques after PCLR.

WEIGHT-BEARING PRECAUTIONS
There were 35 (80%) articles that discussed a specific weight-bearing progression, with all studies recommending a progression based on timeframe following surgery.6,16,17,20-50 Recommendations for non-weight-bearing (NWB) immediately after surgery was included in 12 articles, with duration ranging from two to eight weeks post-operatively.5,16,24-28,32,36,44,45,51 Four studies recommended toe-touch weight-bearing (TTWB) status initially, ranging from 10 days to six weeks.17,21,39,42 Fourteen studies recommended immediate partial or progressive weight-bearing (PWB, ranging from 20-80% full weight-bearing)20,29-31,33,34,37,38,40,41,46-50,52 and six studies suggested full weight-bearing or weight-bearing as tolerated (FWB) immediately following surgery.22,23,33,43,46,47 For studies utilizing restricted weight-bearing status following surgery, only two gave specific details regarding the timeframe for progression to FWB, which ranged from 10 days to 12 weeks .42,44 (Figure 2).

POST-OPERATIVE BRACING
There were 42 articles (95%) that discussed the use of immediate post-operative bracing.6,16,17,20-31,33-59 Thirty of these articles recommended maintaining the knee in full extension while also providing specific timeframes for weaning or discontinuing use of the brace.16,21-30,34,36-39,41,42,44,46,48,49,51-53,55-59 Fifteen of these articles recommended unlocking the brace prior to discharging the patient from the brace,16,23-30,36,37,44,46,52,55,56 while the other fifteen did not specify unlocking the brace.21,22,29,34,36,39,41,42,44,48,49,50,53,56-58 Of the studies recommending unlocking the brace, only four provided specific ranges (degrees) for wearing the brace, which initially ranged from 30-90˚ between one and four weeks post-operatively.30,52,55,56 The timeframe to discontinue brace usage after being locked in extension varied from 1 to 8 weeks post-operatively.49,51,53,58-60 Additionally, one study recommended unlocking the brace at 12 weeks, but was not specific with timeframe for removing the brace.23 Other studies discontinued the brace between six and 12 weeks after the brace was unlocked.16,24,28,30,36,37,44,52,56 Details regarding specific time periods or knee position for brace usage were missing from eight articles.17,20,33,35,40,47,50,54 One author allowed for immediate unrestricted knee motion up to 90˚ flexion within a brace31 while another recommended locking the knee in 15˚ of flexion for a period of eight weeks after surgery.31 While most articles described the use of a simple hinged knee brace, two studies6,45 recommended a PCL specific brace.

RANGE OF MOTION
Thirty-five articles (80%) discussed ROM recommendations following PCLR.6,16,17,21-31,34-39,41-43,45-47,49-50,52,53,55,56,58-60 Four studies recommended passive ROM
Table 1. Summary of Included Studies’ Recommendations on Rehabilitation Milestones and Timeframes following PCL Reconstruction.

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Level of Evidence*</th>
<th>Weight-bearing</th>
<th>Brace</th>
<th>Range of Motion</th>
<th>Hamstring</th>
<th>Running, agility, plyometrics</th>
<th>Return to Sport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accadbled F et al., 2013</td>
<td>IV</td>
<td>PWB initially; FWB by 9 wk</td>
<td>Long leg cast x 6 wk; hinged knee brace x 6 wk</td>
<td>Run: 6 mo</td>
<td></td>
<td></td>
<td>9 mo</td>
</tr>
<tr>
<td>Adler GC, 2013</td>
<td>IV</td>
<td>Extension brace x 1 wk</td>
<td>Delayed; &gt; 1 wk</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bovid KM et al., 2013</td>
<td>IV</td>
<td>Early, limited and protected ROM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9-12 mo</td>
</tr>
<tr>
<td>Cavanaugh JT, 2015</td>
<td>V</td>
<td>TTWB x 2 wk; PWB x 4 wk; FWB by 7 wk</td>
<td>Extension brace x 6 wk</td>
<td>Immediate; 0-90'</td>
<td>6 wk (active)</td>
<td>Agility: 5 mo; Run: 4 mo; Plyo: 4 mo</td>
<td>24 wk§</td>
</tr>
<tr>
<td>Chahla J, 2016</td>
<td>V</td>
<td>NWB x 6 wk; FWB by 7 wk</td>
<td>PCL brace (Jack brace or Rebound brace) x 6 mo†</td>
<td>Immediate; 0-90'</td>
<td></td>
<td>Agility: 6 mo; Run: 6 mo; Plyo: 6 mo</td>
<td></td>
</tr>
<tr>
<td>Chen &amp; Gao 2009</td>
<td>IV</td>
<td>WBAT</td>
<td>Extension brace x 4 wk</td>
<td>Delayed; &gt; 5 wk</td>
<td>Run: 4 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chuang TY et al., 2011</td>
<td>IV</td>
<td>WBAT</td>
<td>Extension brace x 12 wk; unlocked</td>
<td>Delayed; &gt; 4 wk</td>
<td>Run: 4 mo</td>
<td></td>
<td>9 mo</td>
</tr>
<tr>
<td>Deie M et al., 2015</td>
<td>III</td>
<td>&quot;Fixed&quot; brace x 2 wk, PCL brace until 6 mo</td>
<td></td>
<td>Run: 6 mo</td>
<td></td>
<td></td>
<td>10-12 mo</td>
</tr>
<tr>
<td>Eguchi A et al., 2014</td>
<td>IV</td>
<td>NWB x 3 wk; PWB</td>
<td>Extension brace x 1 wk</td>
<td>Delayed; &gt; 1 wk</td>
<td>Run: 4 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fanelli GC et al., 2007</td>
<td>V</td>
<td>NWB x 6 wk; PWB x 3 wk; FWB by 10 wk</td>
<td>Extension brace x 4 wk; unlocked 4-6 wk</td>
<td>Delayed; &gt; 3 wk</td>
<td>Run: 4 mo</td>
<td></td>
<td>9-12 mo</td>
</tr>
<tr>
<td>Fanelli GC et al., 2009</td>
<td>V</td>
<td>NWB x 5 wk; PWB x 4 wk; FWB by 10 wk</td>
<td>Extension brace x 5 wk; unlocked, d/c brace at 10 wk</td>
<td>Delayed; &gt; 6 wk</td>
<td>Agility: 25 wk</td>
<td></td>
<td>37 wk</td>
</tr>
<tr>
<td>Fanelli GC et al., 2010</td>
<td>V</td>
<td>NWB x 5 wk; PWB x 4 wk; FWB by 10 wk</td>
<td>Extension brace x 3 wk; unlocked</td>
<td>Delayed; &gt; 4 wk</td>
<td>6 mo (resisted OKC)</td>
<td></td>
<td>6 mo</td>
</tr>
<tr>
<td>Fanelli GC et al., 2010</td>
<td>V</td>
<td>NWB x 5 wk; PWB x 4 wk; FWB by 10 wk</td>
<td>Extension brace x 5 wk, d/c brace at 10 wk; PCL brace</td>
<td>Delayed; &gt; 5 wk</td>
<td>Run: 4 mo</td>
<td></td>
<td>9 mo</td>
</tr>
<tr>
<td>Fanelli GC et al., 2015</td>
<td>V</td>
<td>NWB x 3 wk; PWB x 2 wk; FWB by 6 wk</td>
<td>Extension brace x 3 wk, d/c brace at 10 wk</td>
<td>Delayed; &gt; 3 wk</td>
<td>Run: 4 mo</td>
<td></td>
<td>9 mo</td>
</tr>
<tr>
<td>Fanelli GC, 2008</td>
<td>V</td>
<td>NWB x 6 wk; PWB x 3 wk; FWB x 10 wk</td>
<td>Extension brace x 3 wk; unlocked</td>
<td>Delayed; &gt; 4 wk</td>
<td>6 mo (resisted OKC)</td>
<td></td>
<td>6 mo</td>
</tr>
<tr>
<td>Garofalo R et al., 2006</td>
<td>IV</td>
<td>NWB x 2 days; FWB x 5 wk; FWB by 8 wk</td>
<td>Extension x 3 wk</td>
<td>Delayed; &gt; 3 days</td>
<td>3 mo (resisted OKC)</td>
<td></td>
<td>9 mo</td>
</tr>
</tbody>
</table>
Table 1. Summary of Included Studies’ Recommendations on Rehabilitation Milestones and Timeframes following PCL Reconstruction. (continued)

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Level of Evidence*</th>
<th>Weight-bearing</th>
<th>Brace</th>
<th>Range of Motion</th>
<th>Hamstring</th>
<th>Running, agility, plyometrics</th>
<th>Return to Sport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gill et al., 2012</td>
<td>IV</td>
<td>PWB x 5 wk; FWB by 6 wk</td>
<td>Extension brace x 2 wk; unlocked; d/c brace at 6; functional brace at 12</td>
<td>Immediate; passive</td>
<td>18 wk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Giombini et al., 2007</td>
<td>V</td>
<td>PWB x 4 wk; FWB by 5 wk</td>
<td>Extension brace x 2 wk; unlocked</td>
<td>Delayed; &gt; 4 days</td>
<td>12 wk (“actively put to work”)</td>
<td>Agility: 7 mo; Run: 5 mo; Plyo: 7 mo</td>
<td>8 mo§</td>
</tr>
<tr>
<td>Goudie et al 2010</td>
<td>IV</td>
<td>TTWB x 6 wk; PWB x 3 wk; FWB by 10 wk</td>
<td>Extension brace</td>
<td>Immediate, auto-assisted ROM exercise</td>
<td>3 - 9 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hermans et al 2009</td>
<td>IV</td>
<td>PWB x 7 wk; FWB by 8 wk</td>
<td>Brace locked in 15° flexion x 4 wk</td>
<td>Delayed; &gt; 4 wk</td>
<td>9 mo§</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huang et al 2010</td>
<td>IV</td>
<td>NWB x 2 wk; PWB x 3 wk; FWB by 6 wk</td>
<td></td>
<td></td>
<td>General: 3 mo; competitive: 4 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Johnson, D 2009</td>
<td>V</td>
<td>PWB x 5 wk; FWB by 6 wk</td>
<td>Extension splint immobilization</td>
<td></td>
<td>12 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim et al 2009</td>
<td>III</td>
<td>PWB x 6 wk; FWB by 7 wk</td>
<td>Extension brace x 2 wk; PCL brace x 6 wk</td>
<td>Delayed; &gt; 2 wk</td>
<td>6 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lee &amp; Jung 2013</td>
<td>V</td>
<td>WBAT</td>
<td>Extension brace</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li et al 2015</td>
<td>IV</td>
<td>NWB x 6 wk; PWB x 5 wk; FWB by 12 wk</td>
<td>Extension brace x 4 wk, d/c brace at 12 wk</td>
<td>Immediate; 0-90°</td>
<td>6 mo</td>
<td>6 mo (light), 9 mo (full)</td>
<td></td>
</tr>
<tr>
<td>Lim et al 2010</td>
<td>III</td>
<td>PWB x 7 wk; FWB by 8 wk</td>
<td>Extension brace x 6 wk</td>
<td>Passive in prone</td>
<td>4 mo</td>
<td>9 mo</td>
<td></td>
</tr>
<tr>
<td>Lim et al 2015</td>
<td>III</td>
<td>PWB x 6 wk; FWB by 7 wk</td>
<td>Extension brace x 6 wk, d/c brace at 12 wk</td>
<td>Immediate; 0-90°</td>
<td>12 wk</td>
<td>Run: 12 wk</td>
<td>9 mo</td>
</tr>
<tr>
<td>MacGillivray JD et al., 2006</td>
<td>III</td>
<td>TTWB x 4 wk; PWB x 2 wk; FWB by 7 wk</td>
<td>Extension brace x 4 wk</td>
<td>“Early post-operative period”: 0-90° (passive)</td>
<td></td>
<td>9 mo</td>
<td></td>
</tr>
<tr>
<td>Maruyama et al 2012</td>
<td>III</td>
<td>PWB x 2 wk; FWB by 3 wk</td>
<td>Extension brace</td>
<td></td>
<td>Run: 6 mo</td>
<td>8 mo</td>
<td></td>
</tr>
<tr>
<td>Marx et al 2009</td>
<td>V</td>
<td>PWB x 4 wk; FWB by 5 wk</td>
<td>Extension brace x 4 wk</td>
<td>Delayed; &gt; 4 wk</td>
<td>4 mo</td>
<td>Run: 6 mo</td>
<td>9 mo</td>
</tr>
<tr>
<td>Puh et al 2014</td>
<td>V</td>
<td></td>
<td>Extension brace x 4 wk; unlocked</td>
<td>Immediate; 0-90°</td>
<td>Run: 6 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quelard et al 2010</td>
<td>IV</td>
<td>TTWB x 1 wk; PWB x 1 wk; FWB by 3 wk</td>
<td>Extension brace x 45 days</td>
<td>Immediate; 0-90°</td>
<td>6 mo (resisted OKC)</td>
<td>Run: 90 days</td>
<td>8 mo</td>
</tr>
</tbody>
</table>
Table 1. Summary of Included Studies’ Recommendations on Rehabilitation Milestones and Timeframes following PCLR Reconstruction. (continued)

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Level of Evidence*</th>
<th>Brace</th>
<th>Range of Motion</th>
<th>Hamstring</th>
<th>Running agility, plyometrics</th>
<th>Return to Sport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranalleta et al 2010</td>
<td>V</td>
<td>WBAT</td>
<td>Brace unlocked to 90°</td>
<td>Immediate; 0-90°</td>
<td>Agility: 7 mo; Run: 5 mo</td>
<td>9 mo</td>
</tr>
<tr>
<td>Seon JK et al., 2006</td>
<td>III</td>
<td>NWB x 7 wk; PWB x 4 wk; FWB by 12 wk</td>
<td>Extension brace x 4 wk, d/c brace at 12 wk</td>
<td>Run: 6 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiridonov et al 2011</td>
<td>IV</td>
<td>NWB x 6 wk; FWB by 7 wk</td>
<td>Jack PCL brace x 6 mo†</td>
<td>Immediate; 0-90°</td>
<td>Run: 6 mo $</td>
<td>9 mo</td>
</tr>
<tr>
<td>Stannard &amp; McKean 2009</td>
<td>III</td>
<td>WBAT</td>
<td>Extension brace x 1 wk; unlocked</td>
<td>Immediate, no restriction</td>
<td>Run: 6 mo</td>
<td>6 mo</td>
</tr>
<tr>
<td>Taylor &amp; Miller 2009</td>
<td>V</td>
<td>WBAT</td>
<td>Extension brace</td>
<td>Begun in prone</td>
<td>Discouraged</td>
<td>Run: 4 mo</td>
</tr>
<tr>
<td>Tornese et al 2008</td>
<td>II</td>
<td>Extension brace x 1 wk; unlocked, d/c brace at 6 wk</td>
<td>Immediate; 0-90°</td>
<td>Medium impact: 8 mo; High impact: 9 mo $</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wong et al 2009</td>
<td>II</td>
<td>PWB x 6 wk; FWB by 7 wk</td>
<td>Extension brace x 4 wk</td>
<td>6 wk</td>
<td>6-12 mo</td>
<td></td>
</tr>
<tr>
<td>Wu et al 2007</td>
<td>IV</td>
<td>PWB x 6 wk; FWB by 7 wk</td>
<td>Extension brace x 1 wk</td>
<td>Immediate; 0-90°</td>
<td>6 wk</td>
<td>6 mo (light), 9 mo (full)</td>
</tr>
<tr>
<td>Xu et al 2014</td>
<td>III</td>
<td>LARS - PWB x 4 wk; FWB by 5 wk; HTG - NWB x 2 wk, PWB weeks x 7 wk; FWB by 10 wk</td>
<td>Protective brace x 8 wk</td>
<td>Delayed; LARS &gt; 1 wk; HTG &gt; 3 wk (0-90°)</td>
<td>LARS: RTS: 2 mo (light), 4 mo (full); HTG: RTS: 4 mo (light), 10 mo (full)</td>
<td></td>
</tr>
<tr>
<td>Zayni et al 2011</td>
<td>III</td>
<td>Extension brace x 45 days</td>
<td>6 mo</td>
<td>Run: 150 days</td>
<td>7 mo</td>
<td></td>
</tr>
<tr>
<td>Zhao &amp; Huangfei 2007</td>
<td>IV</td>
<td>Extension brace x 2 mo</td>
<td>Delayed; &gt; 3 wk (0-120°)</td>
<td>Run: 3 mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhao et al., 2008</td>
<td>IV</td>
<td>Extension brace x 2 mo</td>
<td>Delayed; &gt; 3 wk (0-120°)</td>
<td>Run: 3 mo</td>
<td>12 mo</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: wk, week(s); mo, month(s); NWB, Non-weight-bearing; PWB, PWB, Full weight-bearing; Partial weight-bearing (20-80% Full weight-bearing); D/c, discharge; ROM, range of motion; Plyo, plyometrics; *, Level of evidence based on Oxford Centre for Evidence Based Medicine - Levels of Evidence; †, additional criteria prior to discharge of brace; ‡, additional criteria prior to running; $, additional criteria prior to return to sport

exercises,30,39,52,55 one with auto assisted ROM exercise,17 and the remaining studies were non-specific with type of ROM exercise. Five of these articles did not give details regarding specific timeframes for initiation of ROM exercises.17,30,39,47,60 The remaining articles were classified into two groups based upon the point in rehabilitation that ROM exercises began. The “early ROM” articles were defined as those allowing for immediate ROM exercises post-operatively, while the “delayed ROM” articles were those that initially deferred ROM exercises until a set post-operative time period. (Figure 3)

Early Range of Motion
There were 19 studies that allowed for early ROM following PCLR.6,17,21,29,30,36-39,42,43,45-47,49-52,53,56,60 Despite
all allowing for early knee motion, there were many differences in degrees of motion allowed and progression timeframes. Two articles allowed for unrestricted ROM based upon patient comfort. Recommendations for immediate ROM exercises within a limited range of 0 to ≤ 90˚ of knee flexion was included in 13 articles. From this restricted knee motion, ROM exercise was permitted beyond 90˚ after two to 10 weeks. Two studies allowed for early protected ROM but failed to give specific details regarding motion restrictions and time for progression. Two articles recommended early ROM exercises specifically performed in the prone position without stating restrictions for knee motion. 

**Delayed Range of Motion**

There were 16 studies that recommended delayed ROM following PCLR. Xu and colleagues were the only authors who differentiated recommendations based upon graft type, delaying ROM exercise for one week if undergoing a “Ligament Advanced Reinforcement System” (LARS procedure) and delaying three weeks with hamstring tendon autograft (HTG) procedure. The onset of ROM exercises in the remaining 15 studies varied from one to six weeks post-operatively. There were two studies that began ROM within the first week following PCLR, 2 articles after two weeks, three after three weeks, five after four weeks, two after five weeks and one after six weeks.
Once ROM was initiated, some articles did limit the degree of allowable knee motion to 60˚, ≤ 90˚, and ≤ 120˚. There were 10 articles that allowed for unrestricted motion once ROM exercises began.

Range of Motion Goals
With such variation in onset and progression of ROM exercises, articles were further analyzed for discussion of specific goals for knee ROM milestones. Two articles recommended achieving 60˚ knee flexion by four to five weeks post-operatively, 13 recommended a goal of 90˚ as early as two weeks or as late as 12 weeks post-operatively, and seven recommended 120-130˚ by two to three months. Goals for achieving full knee ROM ranged from as early as six weeks to three months post-surgery.

STRENGTHENING EXERCISES
Hamstring Strengthening
Fifteen studies described recommendations for initiating isolated hamstring exercise following PCLR. Three of these articles recommended hamstring exercises beginning at six weeks post-operatively, with one study specifying “active” knee flexion only. The remaining articles delayed hamstring specific exercises for longer time periods with four studies delaying until three months, two studies delaying until four months, and five studies delaying until six months post-surgery. Four studies specifically recommended delaying open kinetic chain (OKC) knee flexion, ranging from three to six months. Taylor & Miller recommended hamstring activation being “discouraged” in the early post-operative period, but did not specify when hamstring exercise could begin.

Quadriiceps Strengthening
There were 11 studies that outlined specific recommendations for isolated quadriceps strengthening (i.e. OKC knee extension) as part of the PCLR rehabilitation program. The initiation of OKC quadriceps exercises occurred at two weeks, four weeks, six weeks, and 11 weeks.
Two studies recommended OKC exercises, but did not specify timeframes for initiation.35,44

Functional Strengthening
Twenty-three articles (52%) included specific recommendations in regards to timing for the initiation of closed kinetic chain (CKC) exercise.6,16,17,21,23-26,29,30,33-38,41,42,44-46,52,60 Three articles allowed CKC exercises immediately following surgery.21,46,52 Eighteen articles recommended initiating CKC exercises at four weeks,29 six to seven weeks,6,17,30,33,34,36,38,41,42,44-46,49-51 and four months42 following PCLR. Two articles specifically mentioned utilizing CKC exercises but were nonspecific with regards to timing for initiation.35,44

Several authors recommended a restricted range of knee excursion once CKC exercises were initiated.21,24,26,30,35,36,42,45 Four studies limited knee flexion depth to 30-45°,24,26,30,35 while another four studies permitted knee flexion to 60-70°.21,36,42,45

RETURN TO RUNNING, AGILITY AND PLYOMETRIC ACTIVITY
Nineteen studies (43%) provided specific recommendations for initiating running after PCLR.6,20-22,23,24,26,30,33-36,38-40,42,43,45,46,48,49,51,52,54,56,57,60 (Figure 5) Time from surgery was once again cited as a frequent standard for progression with time requirements of four to five months,32,52 six to seven months,21,24,26,46-48,57 eight to nine months,16,20,23,25,27-31,36-43,45,49,56,60 and 10-12 months33,51,54,59 all cited. Kim et al specifically indicated "low impact" sports could begin at six months post-operatively, but did not comment on any further progression beyond this level of play.34 Xu and colleagues50 discussed different timeframes for returning to sports depending upon graft type,
recommending return to sports at four months for LARS and 10 months for HTG.

There were four studies that identified specific goals for strength and functional performance prior to returning to full sports participation.\textsuperscript{21,30,31,56} All of these articles recommended quadriceps or hamstring limb symmetry goals of $> 85\%$ for strength. Functional performance testing using single leg hopping tasks were recommended by three authors, with limb symmetry goals from $85-90\%$.\textsuperscript{21,30,56} Tornese and colleagues recommended that strength and functional performance goals be achieved prior to participation in medium impact sports at eight months post-operatively and high impact sports at nine months.\textsuperscript{56}

**DISCUSSION**

Effective rehabilitation after PCLR is an essential component for optimizing post-surgical outcomes and resuming desired levels of athletic performance. The results of this review illustrate that recommendations for specific components of rehabilitation, functional performance testing, and resumption of activity following PCLR are highly variable. In addition, there are currently no studies that directly compare the efficacy or associated outcomes of these various aspects of rehabilitation protocols and current rehabilitation recommendations are based on low level evidence. This is in striking contrast to intervention strategies (i.e. therapeutic exercises) and performance assessment after anterior cruciate ligament reconstruction (ACLR) which have been more thoroughly investigated.\textsuperscript{61,62}

**WEIGHT-BEARING**

Within the current review, weight-bearing recommendations ranged from no restriction to 12 weeks of limited weight transfer through the limb (Figure 2). The degree of weight transferred through the operated limb is an important rehabilitation consideration because of the need to minimize stress on the PCL graft, while still maintaining optimal health of joint cartilage and to stimulate bone tunnel healing.\textsuperscript{63} Recently, Mook and colleagues analyzed the effects of simulated load variations on acquired PCL graft laxity and found that while PWB status had no effect on graft laxity, FWB in early rehabilitation did correlate with significantly increased graft laxity.\textsuperscript{64} They concluded that rehabilitation protocols should avoid early post-operative weight-bearing as this may contribute to graft laxity and an unstable knee complex. Although this review does suggest some evidence favoring delayed weight-bearing exists, many questions regarding optimal loading after PCLR remain. Future clinical and laboratory-based research studies are necessary to determine optimal post-operative weight-bearing and progression following PCLR.

**BRACING AND RANGE OF MOTION**

There appeared to be the most consensus among authors regarding the need for protected mobility after PCLR, with 95\% of articles recommending a period of bracing post-operatively. The use of bracing was typically coupled with specific recommendations regarding knee motion exercises after surgery. The principle theory for restricting knee motion following PCLR lies in biomechanical studies that have demonstrated tension in portions of the PCL, increasing with increasing knee flexion motion,\textsuperscript{43,65,66} and notions that early flexion mobilization after PCLR may be associated with graft stretching and knee instability.\textsuperscript{64} In accordance, the majority of studies included in this review support a gradual, flexion ROM program after PCLR.

Despite global adherence to this principle, there is significant variability in ROM exercise prescription related to the timing of introducing motion exercises (immediate versus delayed) and the degree of allowable motion permitted. In addition, there was variation in positional preferences, with some protocols specifically limiting knee ROM exercises to prone only and utilization of posterior tibial supports out of further concern for graft stress.\textsuperscript{21,30,37,55}

Currently, there are no studies evaluating the effect of different ROM protocols on clinical outcomes after PCLR. While graft protection is important, unnecessarily restricting knee motion could lead to difficulty restoring knee motion, prolonged rehabilitation, increased likelihood of arthrofibrosis and limited patient satisfaction.\textsuperscript{67,68} Research studies comparing outcomes associated with early versus delayed knee motion and varying ROM exercise protocols are necessary in order to provide clinicians with improved evidence to empower clinical decision making regarding this important aspect of rehabilitation.
STRENGTHENING EXERCISES

Exercise selection is an important consideration following knee surgery in order to properly balance the goals of graft protection with muscular activation and strengthening.69,70 The initiation of isolated hamstring strengthening after PCLR is among one of the most highly debated aspects of rehabilitation. Contraction of the hamstrings can create deleterious posterior shear forces within the tibiofemoral joint, compromising the integrity of healing PCL graft.71 As a result, hamstring contraction and strengthening exercises have been discouraged in the early phases of PCLR rehabilitation. Although most articles agreed upon this principle of deferring resisted hamstring exercises, there were only 14 studies providing specific recommendations to initiate hamstring exercise. Additionally, timing for beginning hamstring strengthening was highly variable, ranging from six weeks to six months.21,24,26,36,42,48,49,57 Further research is necessary to more fully understand the implications of varying types of hamstring exercises and the timing of initiation of those exercises on graft integrity and knee stability. Research of this nature will help direct rehabilitation professionals in more precise exercise prescription for optimizing hamstring strength recovery, which is necessary for normalizing knee biomechanics and promoting return to activities after surgery.72

With regard to initiating OKC or CKC exercises, there were some common trends that emerged during this review. Nearly half of the studies emphasized quadriceps strengthening as an important aspect of rehabilitation, likely due to the role quadriceps strength has in maintaining knee stability, providing PCL graft protection, resuming athletic activity and reducing the potential for subsequent knee injuries.69,70,73-75 Restricted knee flexion motion from 0-50˚ with both OKC and CKC exercises has been found to minimize strain on the PCL.13,37,71 Exercises allowing proper co-contraction of quadriceps and hamstrings muscle groups (e.g. mini-squats, short arc leg press) are commonly recommended within this protective range to balance strengthening gains and graft protection.77,71,76 Despite this understanding, the results of this review show a large degree of variation in onset and permitted joint excursion with both OKC and CKC strengthening exercises. Future laboratory studies are needed to better understand the effects of specific OKC and CKC exercises on PCL graft integrity, while clinical research is needed to determine optimal timing and strength gains produced through varying exercise prescriptions. This information is essential as some studies have identified persistent quadriceps weakness up to 24 months following PCLR and deficits in quadriceps strength may lead to sub-optimal functional outcomes.17,21,30,31,56

Optimizing exercise prescription through evidence informed practice may help improve outcomes within this population.

LATE PHASE REHABILITATION AND RETURN TO SPORTS

As the majority of PCLR surgeries occur in athletes, it is important to incorporate appropriate and safe return of higher level activities into the rehabilitation program.10 The results of this review indicate that the decision to initiate a running, agility and plyometric training program was frequently based on timeframe from surgery alone. Only two studies recommended objective strength criteria be achieved in order to initiate a running program.30,31 Quadriceps and hamstring strength criteria have been frequently cited as requirements for activity progression following ACLR, as deficits in strength may lead to reduced knee stability when progressing to these activities.77-80 Thigh muscle strength deficits similar to those found after ACLR have also been reported following PCLR,17,75,81 however, specific strength goals seem to be under-utilized to support rehabilitation progression post-PCLR.

With regards to return to unrestricted sports, most protocols included within this review once again relied heavily upon time-based criteria, which were highly variable, ranging from four to 12 months post-operatively. There were nine studies that outlined some type of strength and/or functional goals to support the decision to return to sport,6,20,21,27,30,31,39,45,48 however, only three of these articles included enough detail for practical clinical application.21,30,31 Although outcomes with return to sport have not been commonly researched after PCLR, a combination of timeframe, strength and functional performance measures (e.g. unilateral hop tests) have been advocated as screening tools post-ACLR to help
reduce risk of re-injury upon return to sports.\textsuperscript{70,79,82} Similar goals of optimizing strength return and functional performance while allowing adequate time for graft maturity, would likely contribute to optimal outcomes following PCLR. However, more research is needed to provide specific recommendations and better support this theory.

There are several limitations to this review. First, the current literature review consisted of rehabilitation protocols following isolated PCLR only. Concomitant injuries and additional procedures are common within this population and may require different rehabilitation strategies than those discussed in this review. In addition, the level of evidence outlining rehabilitation recommendations following PCLR is weak, as it is currently based primarily on principles of physiological healing, biomechanical modeling and personal opinion. Research related to rehabilitation following PCLR is not as common as other knee injuries, likely due to the low incidence of PCL injury. Thus, the results of this review should be interpreted within the context of literature available for review. In addition, multiple entries with the same primary author(s) were included within this study. Although this decision may bias the results of this review towards specific authors, the authors of this review chose to include these studies as the protocols outlined under the same primary author did have specific differences within them, and it was felt inclusion of these articles gave the most accurate reflection of what exists within the published literature. Nonetheless, it should be noted that this decision may bias the results of this review towards the opinions of those authors. Finally, this review included literature published only within the past 10 years. The authors felt that this limitation was necessary in order to limit any differences in rehabilitation protocols that may exist due to evolving surgical techniques and graft types. However, it should be noted that any pre-existing literature beyond our inclusion criteria was not included within this review.

**CONCLUSION**

Post-surgical rehabilitation strategies and effective decision making for safe return to sports are important considerations for sports medicine practitioners, as athletes represent a large proportion of those undergoing PCL reconstruction.\textsuperscript{8,8,3,10} Currently, only low level evidence exists to support rehabilitation recommendations following PCLR. Although there is some level of agreement in the literature related to restrictions in weight-bearing, range of motion, brace usage or strengthening exercise prescription, there is no consensus regarding optimal administration and specific application of these factors. The majority of rehabilitation progression goals were based on post-operative timeframes, with few articles outlining specific objective criteria to provide for more detailed clinical decision making. Additional studies should be conducted to prospectively evaluate rehabilitation protocols in order to establish improved rehabilitation guidelines incorporating graft protection, optimal loading, exercise strategies and readiness to return to higher level activities.

**REFERENCES**


ABSTRACT

Background: Sternoclavicular (SC) joint instability is a rare injury, but one with profound implications given its proximity to vital structures and function as the only true articulation between the upper extremity and axial skeleton. The majority of SC joint instability can be treated non-operatively; however, there is a role for reconstruction in the presence of instability that results in pain and dysfunction that is refractory to conservative management or deformity resulting in functional impairment. Given the lack of inherent osseous stability at the sternoclavicular joint and the role of ligaments as primary stabilizers, surgical intervention with emphasis on ligament reconstruction may be recommended. Safe and effective rehabilitation is conducted through phase progression, with avoidance of premature stress to the healing soft tissue graft. The purpose of this clinical commentary is to provide the senior author's rehabilitation protocol, which utilizes the available scientific literature to inform phase content and progression.

Key words: clavicle, reconstruction, rehabilitation, return to sport, sternoclavicular joint

Level of Evidence: 5
INTRODUCTION
Sternoclavicular (SC) joint injury is rare and comprises 0.5% to 3% of shoulder girdle injuries.\textsuperscript{1-3} Given its proximity to vital neurovascular structures immediately posterior and the SC joint’s function as the only true articulation between the upper extremity and axial skeleton, the potential for serious complication and long-term disability exists if the injury is missed. In the acute setting, posterior dislocations of the SC joint are potentially severe and occasionally life-threatening.\textsuperscript{4,5} Management of sternoclavicular joint pathology mandates a working knowledge of regional anatomy, particularly the soft tissue stabilizers, for appropriate management and rehabilitation. The purpose of this clinical commentary is to provide the senior author’s rehabilitation protocol, which utilizes the available scientific literature to inform phase content and progression.

ANATOMY
The sternoclavicular joint is diarthrodial in nature, characterized by an articulation of the medial clavicle with the manubrium of the sternum (Figure 1). The articular surface area of the clavicle is much larger than that of the sternum and both ends are covered with hyaline cartilage.\textsuperscript{6} Lee et al\textsuperscript{7} performed a detailed quantitative anatomical description of the sternoclavicular joint. Approximately 67% of the medial clavicle contains articular cartilage and even less articulates with the angle of the sternum\textsuperscript{7}. The intraarticular disk, a thick and fibrous structure, is interposed between the surfaces of the clavicle and the sternum. Despite the saddle-type joint created by the bulbous, convex medial clavicle and the clavicular notch of the sternum, there is very little osseous restraint given the shallow socket and often incongruent articulation.

Given the inherent incongruity of the joint, the sternoclavicular joint relies primarily on a network of ligamentous attachments for strength and stability. The costoclavicular ligament is the largest ligament of the sternoclavicular joint with a reported average length of 1.3 cm and a maximum width of 1.9 cm.\textsuperscript{7,8} The costoclavicular ligament extends from the inferior surface of the medial end of the clavicle, the rhomboid fossa, to provide a point of attachment to the first rib adjacent to its synchondral attachment to the sternum.\textsuperscript{9} The interclavicular ligament connects the superior capsular ligaments of the sternum with the superomedial borders of the clavicles. This ligament serves as a restraint against superior translation of the clavicle during shoulder adduction and extension.\textsuperscript{10} The costoclavicular and interclavicular ligaments are thought to be auxiliary stabilizers of the SC joint with little effect on anterior or posterior translation.\textsuperscript{11}

The capsular ligament extends from the anterosuperior to the posterior aspect of the joint and represents a thickening of the joint capsule. The posterior sternoclavicular ligament and the costoclavicular ligaments are the strongest.\textsuperscript{11,12} A post-mortem anatomic study by Bearn et al\textsuperscript{12} suggests that the capsular ligament is the most important ligament for maintaining

the position of the clavicle. In this study, sectioning of the capsular ligament alone resulted in inferior displacement of the clavicle, while division of the other ligaments did not influence clavicle position. Another study demonstrated that the posterior capsule is a major stabilizer against both anterior and posterior translation while the anterior capsule acts as a secondary stabilizer against anterior translation alone. The subclavius muscle has been proposed as an important stabilizer of the sternoclavicular joint. These observations suggest that preservation of the subclavius muscle warrants special attention during surgery of the SC joint as it contributes to additional stability in the presence of ligamentous injury.

Biomechanics
The lack of osseous constraint contributes to a free range of motion of the SC joint through all planes, including rotation. Motion through the SC joint has been described as 30-35 degrees of elevation with a combined range of 35 degrees anterior and posterior translation. The SC joint acts as the hinge and the clavicle as a lever for the shoulder girdle. Accordingly, patients with a short clavicle will experience significantly more torque across the SC joint. These combined movements allow 45-50 degrees of rotation along the long axis. It is important to remember that all forces placed through the joints of the shoulder girdle, especially during above head activity, are transferred proximally through the SC joint. The clavicle elevates approximately four degrees for every 10 degrees of arm forward flexion.

DIAGNOSIS
Patient Presentation
Ligamentous injury to the SC joint may occur secondary to direct impact to the anteromedial clavicle or from an indirect force to the ipsilateral shoulder or arm. The patient with acute injury of the SC joint often has severe pain localized to the sternoclavicular joint, increased with any movement of the arm. Posterior dislocation of the SCJ may be caused by a direct impact to the anteromedial aspect of the clavicle or through an indirect force to the posterolateral shoulder, while anterior dislocation is usually due to a lateral compressive force to the shoulder girdle. Upon examination, the patient commonly supports the injured upper extremity in a position of adduction across the trunk, supported with the uninjured arm. The affected upper extremity may appear shortened compared to the contralateral extremity and thrust forward, and the patient commonly experiences increased discomfort when lying in the supine position. With anterior dislocation, the medial end of the clavicle may be visibly displaced and more pronounced on the injured side. With posterior displacement, the usual fullness of the anteromedial chest may be less pronounced. In patients with partially preserved function after dislocation, positions of discomfort may include the cocking position of throwing, particularly with anterior instability. Pain secondary to posterior instability of the SC joint may be less easily reproduced and the deformity may be obscured by swelling. The index of suspicion for the treating clinician to recognize an anterior or posterior SC joint dislocation must be high, as the only presenting symptom may be subtle pain in the area of the SC joint, mild shortness of breath, hoarseness, or tightness in the throat; however these may portend more significant issues including tracheal or esophageal compression, pneumothorax, compression of the great vessels, and thoracic outlet syndrome. On rare occasions, a posterior SC joint dislocation may result in more severe dyspnea, dysphagia, paresthesias and/or neurologic deficits of the affected extremity compared to an anterior SC joint dislocation.

The osseous development of the medial clavicle must be considered when evaluating injuries to the SC joint. The clavicle is the first long bone in the body to ossify (fifth intrauterine week). The epiphysis at the medial end of the clavicle is the last of the long bones to ossify (18th-21st year) and does not fuse with the shaft of the clavicle until the 23rd to 25th years. Other authors suggest an even later age of bony union. Accordingly, the possibility of dislocation through the medial clavicle physis should be considered in the evaluation of younger patients.

IMAGING
Traditional anteroposterior (AP) or posteroanterior (PA) radiographs of the chest and sternoclavicular joints may suggest injury, but are often hard to interpret given the overlay of the clavicle, sternum, and the first rib. CT is the preferred imaging modality to assess problems of the SC joint (Figure 2). CT is
most sensitive and specific for distinguishing injuries to the joint from injuries of the medial clavicle as well as revealing instability manifesting in subtle subluxation of the joint.27,28 Given the incongruent nature of the osseous anatomy of the SC joint, it is essential to obtain CT imaging through both SC joints and the medial half of both clavicles for comparison. This imaging can be combined with dynamic stress testing to further describe sternoclavicular joint disease.29

MRI may be useful in the diagnosis of injury to the soft tissues surrounding the joint as well as injury to the intraarticular disc. Given the relatively late ossification of the medial clavicle and the potential for physeal injury in patients under 30 years of age, MRI may also play a role in determining if the epiphysis has been displaced with the clavicle or is still adjacent to the sternum following trauma. Furthermore, the use of MRI to limit radiation exposure in children with suspected sternoclavicular joint injury has been advocated.30

**SURGICAL MANAGEMENT**

Numerous surgical techniques have been used to treat sternoclavicular joint instability. The senior author prefers reconstruction using hamstring tendon graft in a figure-of-eight fashion since this technique has been shown to be biomechanically superior to other methods when comparing graft integrity, load to failure, and translation of the medial clavicle.31,32 Martetschlager et al. has previously described this method in detail.32 After confirming the hypermobility of the medial clavicle during the examination under anesthesia, the SC joint is exposed along with the medial third of the clavicle. A medial clavicle excision is performed if the SC joint is arthritic.33,34 The hamstring autograft (usually gracilis tendon) is harvested using standard technique, whip-stitched at both ends with non-absorbable, high strength suture and measured to determine the appropriate drill tunnel diameter. Following careful dissection of the retrosternal space and placement of a malleable retractor beneath the medial clavicle and sternum to protect mediastinal structures, two bone tunnels are drilled each in medial clavicle and sternum. The graft is shuttled through passing sutures in the tunnels in a figure-of-eight fashion and secured with non-absorbable, high strength sutures through the tendon knot (Figure 3). A recent study by Petri et
al evaluated 21 sternoclavicular joint reconstructions using the above described technique after a mean of two years and showed significant improvement in clinical outcomes, such as range of motion and strength, with high patient satisfaction and no intra- or postoperative complications.35

**REHABILITATION**

There is a lack of well-examined research protocols following SC joint stabilization available in the literature. The post-operative rehabilitation protocol for sternoclavicular joint reconstruction employed at the senior author’s institution emphasizes avoidance of scapular protraction and retraction (Appendix 1).35 Progression of the protocol should be performed under careful supervision of the rehabilitation team, with attention to achieving and maintaining proper scapulothoracic mechanics. Persistent or recurrent pain and/or swelling at the surgical site indicate inappropriate phase progression.

**Early Recovery (Weeks 0 to 6)**

A sling will be worn for a minimum of six weeks. An active compression cold therapy device, for example the Game Ready® system (Game Ready®, Concord, Georgia U.S.A.), is utilized. The proposed benefits of cryotherapy include edema control, local vasoconstriction and pain reduction.36-38 Multiple cryotherapy modalities have been shown to be effective for short-term pain reduction.38 The senior author prefers active compression cold therapy for 30 minutes, followed by 60 minutes off to avoid skin irritation. The on-off cycle is repeated throughout the day while the patient is awake. After reconstruction of the sternoclavicular joint, patients must avoid scapular protraction and retraction, as well as scapular depression and elevation during the initial six weeks.

Lifting or carrying objects with the affected extremity is not permitted, although range of motion of the elbow, wrist, and hand should be initiated immediately to avoid stiffness in distal joints. Cervical range of motion exercises are also encouraged to avoid stiffness and muscular spasm. Glenohumeral joint motion will begin at six-weeks post-operative. While there is a deficiency of data regarding glenohumeral stiffness after sternoclavicular joint reconstruction, one of the most reported complications is stiffness following shoulder immobilization after rotator cuff repair with an incidence of 4.9% to 32.7%.39-41 Post-operative stiffness following SC joint stabilization is likely multi-factorial and may be secondary to post-operative immobilization, the tear type, presence of capsular adhesions or contractures, as well as patient co-morbidities. Given the duration of immobilization, the authors emphasize passive glenohumeral range of motion.

Isolated hamstrings activation is not permitted for four weeks after surgery to protect and aid in the recovery of the autograft site. Implementation of a walking program is encouraged to both aid in deep venous thromboembolism prevention as well as initiate functional strength recovery in the lower extremities.

**Progression of Rehabilitation Phases**

**Weeks 6 to 12**

Full passive and active-assisted range of motion (AAROM) exercises begin at approximately six weeks (Appendix 1), with active range of motion commencing at eight weeks. Only passive and AAROM are allowed until eight-weeks post-operative. The goal of this second phase is to restore glenohumeral range of motion and promote proper scapulothoracic motion. A contraindication to progression of the protocol includes persistent or recurrent pain and/or swelling. Correction of underlying scapulothoracic dyskinesia will allow normal biomechanics of the shoulder girdle during upper extremity elevation. Aqua therapy, if able, should be incorporated for gentle AAROM. Examples of independent stretches are also provided (Appendix 1, Figures 4a, 4b).

Active ROM begins at 8 weeks after surgery and focuses on strengthening of the shoulder and scapular stabilizers (Figures 5a, 5b). Light isometrics, including internal and external rotation, elbow flexion and extension are also initiated at the eight-week mark. Clinicians should include both open and closed kinetic chain exercises (Figure 6) beginning at this time as well, as electromyographic activity of shoulder girdle musculature demonstrates significant differences when activated in exercises are performed in an open versus closed kinetic chain conditions.42,43
Weeks 13 to 20
The focus of this phase of rehabilitation is to increase the strength of the shoulder musculature with emphasis on proper scapulothoracic motion. Progression of weight and resistance level of the existing exercises is the focus of weeks 13 to 20, including the incorporation of functional lower extremity exercises. Patients may progress to full upper extremity weight bearing activities of daily living without restriction.

Return to Sport/Activity
Functional movement patterns that incorporate the upper and lower body and core are integrated in the final stages of rehabilitation. For patients who wish to return to sport, sport-specific drills may be designed by the supervising physical therapist. These drills are created with the goal of gradual transition to sport specific movements in order to avoid excessive stress at the sternoclavicular joint. Criteria for return to sports participation include no pain with sport-specific exercises, full and painless range of motion, and strength within 10% of the contralateral upper extremity. While multiple evaluation tests of the upper limb are available for the clinician to ascertain readiness of an individual to return to sport, there are no established tests focused on

Figure 4a and 4b. External Rotation Stretch (4a) and Sleeper Stretch (4b)
Controlled, gentle external rotation stretch with assistance via a ski pole (4a) and modified sleeper stretch to stretch the posterior capsule (4b).

Figure 5a and 5b. Prone Scapular Stabilization
Prone strengthening of the scapular stabilizers via shoulder and torso extension.
return to sport following sternoclavicular joint reconstruction. It is the duty of the rehabilitation staff to establish return to sport readiness.

SUMMARY

Many sternoclavicular joint injuries are managed non-operatively. In the cohort of patients who suffer chronic, painful instability, however, reconstruction of the sternoclavicular joint may be beneficial for pain reduction and improving function. Successful return to full activities requires protection of the reconstruction during the early phase of rehabilitation followed by supervised progression through a structured post-operative rehabilitation protocol. The senior author's proposed rehabilitation protocol utilizes the available scientific literature to inform phase content and progression in order to enable safe and effective post-operative rehabilitation.

REFERENCES


### Phase I

**0 to 6 weeks after surgery**

<table>
<thead>
<tr>
<th>Precautions:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No lifting or carrying objects</td>
<td></td>
</tr>
<tr>
<td>No scapular retraction or protraction</td>
<td></td>
</tr>
<tr>
<td>No scapular depression or elevation</td>
<td></td>
</tr>
<tr>
<td>No passive range of motion of the glenohumeral joint</td>
<td></td>
</tr>
<tr>
<td>No isolated hamstrings activation (donor graft site) x 4 weeks</td>
<td></td>
</tr>
<tr>
<td>Weight bearing as tolerated in bilateral lower extremities</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Goals:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain motion at elbow/wrist/hand</td>
<td></td>
</tr>
<tr>
<td>Protect reconstruction/graft site</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Therapeutic Exercises:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical range of motion</td>
<td></td>
</tr>
<tr>
<td>Elbow/wrist/hand range of motion</td>
<td></td>
</tr>
<tr>
<td>Walking program (DVT prevention)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activities of Daily Living (ADL):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ok to work on computer with supported arm</td>
<td></td>
</tr>
<tr>
<td>Elbow motion okay for eating/drinking</td>
<td></td>
</tr>
<tr>
<td>Unaffected arm for primary ADL use</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criterion for Progression:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Absence of persistent or recurrent pain and/or swelling</td>
<td></td>
</tr>
</tbody>
</table>

*DVT: deep vein thrombosis*

### Phase II

**6 to 12 weeks after surgery**

<table>
<thead>
<tr>
<th>Precautions:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No lifting or carrying objects &gt; 5 lbs until 9 weeks post-operative</td>
<td></td>
</tr>
<tr>
<td>No overhead activities (except ROM) until week 8</td>
<td></td>
</tr>
<tr>
<td>No active ROM until 8 weeks</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Goals:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Restore passive and active glenohumeral range of motion</td>
<td></td>
</tr>
<tr>
<td>Promote proper scapulothoracic motion</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Therapeutic Exercises:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapular retraction-depression</td>
<td></td>
</tr>
<tr>
<td>Aqua therapy for gentle AAROM</td>
<td></td>
</tr>
<tr>
<td>Passive ROM on glenohumeral joint</td>
<td></td>
</tr>
<tr>
<td>Active Assist ROM:</td>
<td></td>
</tr>
<tr>
<td>o Internal and external rotation</td>
<td></td>
</tr>
<tr>
<td>o Forward elevation and scaption</td>
<td></td>
</tr>
<tr>
<td>Light isometrics:</td>
<td></td>
</tr>
<tr>
<td>o Internal and external rotation</td>
<td></td>
</tr>
<tr>
<td>o Biceps and triceps</td>
<td></td>
</tr>
<tr>
<td>o Hamstrings isometrics</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix 1. Sternoclavicular Joint Reconstruction Rehabilitation Protocol. (continued)

| • Active ROM (begin at 8 weeks), examples included below**
|---|
|   - Sidelying external rotation
|   - Forward elevation and scaption
|   - Prone horizontal abduction with external rotation
|   - Prone lower trapezius to 60 degrees
|   - Prone extensions with external rotation
|   - Open chain proprioception
|   **Specific exercise examples have been outlined, however, therapists may choose to modify these exercises while maintaining the particular exercise goal.

| • Low load prolonged stretching
|---|
|   - Door jam/pectoralis stretch
|   - Sleeper stretch
|   - 90/90 external rotation stretch
|   - Hamstrings doorway stretch

| Activities of Daily Living (ADL):
|---|
|   • Ok to work on computer with supported arm
|   • Overhead activities may begin at week 8
|   • Dressing/Bathing tasks may be performed with affected arm

| Criterion for Progression
|---|
|   • Full, painless passive and active range of motion

*ROM: range of motion

**Specific exercise examples have been outlined, however, therapists may choose to modify these exercises while maintaining the particular exercise goal.

#### Phase III

| 13 to 20 weeks after surgery
|---|
| Precautions:
|   • None

| Goals:
|---|
|   • Maintain proper scapulothoracic motion
|   • Increase strength of shoulder and peri-scapular musculature

| Therapeutic Exercises:
|---|
|   • Active ROM → Progress to with weight/resistance, examples included below*
|   |   - Sidelying external rotation
|   |   - Forward elevation and scaption
|   |   - Prone horizontal abduction with external rotation
|   |   - Prone lower trapezius to 60 degrees
|   |   - Prone extensions with external rotation
|   |   - Open chain proprioception
|   |   - Functional lower extremity strengthening
### Appendix 1. Sternoclavicular Joint Reconstruction Rehabilitation Protocol (continued)

<table>
<thead>
<tr>
<th>Low load prolonged stretching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doorway pectoralis stretch</td>
</tr>
<tr>
<td>Cross arm stretch</td>
</tr>
<tr>
<td>Sleeper stretch</td>
</tr>
<tr>
<td>90/90 external rotation stretch</td>
</tr>
<tr>
<td>Hamstrings doorway stretch</td>
</tr>
</tbody>
</table>

**Activities of Daily Living (ADL):**
- Full ADLs without restriction

**Criterion for Progression**
- Proper scapulothoracic mechanics with overhead activities
- 5/5 strength upon testing of the rotator cuff, deltoid, trapezius (upper/middle/lower), biceps and triceps musculature

**Phase IV**
- 20+ weeks after surgery

**Precautions:**
- None

**Goals:**
- Maintain proper scapulothoracic motion
- Return to preferred sport/activities

**Therapeutic Exercises:**
- Maintenance strengthening program (2x/week)
  - Sidelying external rotation
  - Forward elevation and scaption
  - Prone horizontal abduction with external rotation
  - Prone lower trapezius to 60 degrees
  - Prone extensions with external rotation
  - Open chain proprioception
  - Functional lower extremity strengthening
- Maintenance stretching program (5-7x/week)
  - Door jam/pectoralis stretch
  - Cross arm stretch
  - Sleeper stretch
  - 90/90 external rotation stretch
- Sport-specific exercises

**Activities of Daily Living (ADL):**
- Full ADLs without restriction

**Criterion for Progression**
- Return to sport based on ability of patient to perform sport-specific exercises pain-free and with proper mechanics.

*Specific exercise examples have been outlined, however, therapists may choose to modify these exercises while maintaining the particular exercise goal.*
ABSTRACT

Roller massage (RM) has become a popular intervention used by rehabilitation professionals and active individuals. The emerging popularity has resulted in the production of various types of rollers and a growing body of research on the therapeutic effects and science behind RM. Despite the growing popularity and research, there is no consensus on clinical standards such as describing the intervention, indications, precautions, contraindications, and assessment. There have been no specific peer reviewed publications that have discussed such standards. This leaves a gap in the knowledge regarding how clinicians are integrating the RM research into their clinical practice. The purpose of this clinical commentary is to discuss proposed clinical standards for RM. Part I will discuss the proposed clinical standards and Part II will report the results of a 20-question survey sent to physical therapy (PT) professional members of the Orthopedic and Sports Physical Therapy Sections of the American Physical Therapy Association.

Key Words: foam roller, massage, muscle soreness, myofascial, release, perceived pain, recovery

Level of Evidence: 5
INTRODUCTION
Roller massage (RM) often also referred to as self-myofascial release (SMR) has become a popular intervention for rehabilitation professionals and active individuals. The growing popularity has stimulated a surge in product development which has produced rollers of varying density, shape, and texture. These devices can be seen in many clinical, fitness, and retail settings. An annual survey by the American College of Sports Medicine reported that RM has been one of the top 20 fitness trends the past two years (2016, 2017). The RM research has also grown throughout the past 10 years with researchers examining the therapeutic effects and basic science behind the intervention.

Despite the growth in products and research, there seems to be a lack of discussion regarding the therapeutic benefits of RM and clinical standards such as describing the intervention, indications, precautions, contraindications, and assessment. A recent search of peer reviewed literature (May 2018) from electronic databases: PubMed, PEDro, Science Direct, and EBSCOhost revealed no specific manuscripts discussing these topics. Other myofascial interventions such as therapeutic massage have published utilization and safety guidelines. For example, the traditional East Asian instrument assisted massage Gua sha has a body of literature discussing the intervention including treatment protocols, side effects, and safety standards. Unfortunately, RM lacks such clearly stated guidelines which creates a challenge for rehabilitation professionals who prescribe RM as an intervention and need to advise clients on proper technique and safe use of the device.

There is a need to develop best practice standards through a universal consensus on describing the intervention, indications, precautions, contraindications, and assessment of RM. The purpose of this commentary is to discuss proposed clinical standards for RM. The authors would like to encourage other rehabilitation professionals and researchers to contribute their expertise to the development of such guidelines. Due to the lack of standards, this commentary will synthesize and reference the best existing evidence from other manual and myofascial therapies as they relate to this discussion. Part 1 of this commentary series will be divided into four content areas: description, indications, precautions & contraindications, and assessment.

DESCRIPTION
For the past 10 years, the intervention has often been referred to as SMR in the literature which may not clearly represent the intervention. The term SMR may be challenging to accept given the growing body of knowledge that alludes to more comprehensive responses from the body. A representative description of SMR is warranted to clearly communicate the intervention to clients and fellow professionals. The description of SMR should be considered a “work in progress” and evolve over time as the knowledge of the intervention grows.

To classify rolling as an “SMR” intervention may not represent what is physiologically occurring during or after the intervention. This presents a challenge since the term “release” alludes to a “setting free” of the myofascial tissues which has long been used with manual myofascial release which is a skilled intervention applied with the rehabilitation professional’s hands. RM consists of the client simply rolling on a device or a rehabilitation professional or individual using a device to providing direct tissue massage versus the skilled practice of manual myofascial release which includes both direct and indirect techniques.

Furthermore, the term “release” may be contrary to the current body of knowledge that suggests that the direct roller pressure may produce a mechanical and global neurophysiological responses that influence tissue relaxation and pain in the local and surrounding tissues through afferent central nervous system (CNS) pathways. These responses may be triggered by low, moderate, or high roller pressure lending evidence to the sensitivity of the myofascia to external forces. For the mechanical effect, the direct roller pressure may change the viscoelastic properties of the local myofascia by mechanisms such as thixotropy (reduced viscosity), reducing myofascial restriction, fluid changes, and cellular responses. Researchers have also found that rolling reduces local arterial stiffness, increases arterial tissue perfusion, and improves vascular endothelial function which are all related to local physiological changes. For the neurophysiological effect, the direct...
Roller pressure may influence tissue relaxation and pain in the local and surrounding tissues. For tissue relaxation, the roller pressure may induce a greater myofascial relaxation or “stretch tolerance” through CNS afferent input from the Golgi tendon reflex and mechanoreceptors. For pain, researchers have postulated that roller pressure may modulate pain through stimulation of cutaneous receptors (e.g. C-tactile fibers), mechanoreceptors, afferent central nociceptive pathways (gate theory of pain), and descending anti-nociceptive pathways (diffuse noxious inhibitory control). Researchers have found that RM decreases evoked pain and reduces spinal-level excitability which provides evidence for these theories. Based upon this, the term “release” may not represent the current theories that allude to a complex mechanical and neurophysiological response that may occur from this intervention.

Perhaps, SMR needs to have better terminology to define what is currently known about this intervention. One suggestion is to change the terms “self-myofascial release or SMR” to “roller massage or RM” which provides a more general classification and is characteristic of the many types of rollers available to consumers. This may have clinical implications when helping clients to understand the differences as well as for insurance payers to correctly categorize the intervention for reimbursement purposes. For example, rehabilitation professionals may explain to clients that self-administered RM is a therapeutic activity and manual myofascial release is a skilled manual therapy and bill the insurance accordingly. Several researchers have begun to implement nomenclature changes in their peer reviewed publications by using the term “roller massage”, “self-massage”, or directly naming a device such as a “foam roller”. The diversity of rollers and what is currently known about the intervention should be represented in a general term such as RM since the prior term SMR could be misleading to clients.

Besides developing a more representative term, a working description or explanation is warranted to clearly communicate the intervention. In contrast to RM, therapeutic massage and manual myofascial release have more specific descriptions that have been published. For example, therapeutic massage has been described as “the systematic and scientifically based manipulation of the soft-tissues of the body by a trained professional.” Manual myofascial release has been described as a “direct-indirect technique involving balancing the structure in 3 planes of motion and making positional corrections that are thought to lead to tissue relaxation” or “a specialized massage technique employed to treat a variety of chronic disorders in which the muscle tissue is stretched and manipulated to relieve tension in the fascia, the thin tissue covering the muscle fibers.” The current evidence on therapeutic massage and manual myofascial release suggests they both produce physiological and therapeutic benefits which are represented in their descriptions.

A proposed description for RM may include the following: “roller massage is a type of self or assisted massage that uses a device to manipulate the skin, myofascia, muscles, and tendons by direct compression.” A working description such as this may provide a clear understanding of the intervention and should evolve as the knowledge of RM grows over time (Table 1). Rehabilitation professionals are encouraged to build upon their own knowledge and help better define and describe RM to their clients and fellow clinicians.

**INDICATIONS**

Currently, there is no consensus on the optimal RM intervention including: type of roller, density, technique, treatment parameters, applied pressure, and cadence. Despite the lack of universal agreement, the existing literature does support the use of RM as a short-term intervention strategy for several conditions (Table 1).

**Warm-up.** The research supports the use of RM as a pre-exercise warm-up since it has been shown to produce no negative effects on performance. Researchers have also found that rolling at 10 minute intervals following a warm-up preserved the range of motion (ROM) increases for 30 minutes after the warm-up to a greater degree than no additional rolling with no negative effects on performance. Researchers have also found that continued rolling between bouts of exercise may decrease muscle performance which should be considered...
when prescribing RM as a warm-up or intersession activity. Thus, using RM as part of a warm-up may be a viable option for some individuals. Further investigations are needed to validate these findings.

**Post-exercise recovery.** The current research does support the use of RM for post-exercise recovery. Several researchers have found that post-exercise RM may reduce decrements in muscle performance, increase posttreatment pressure pain thresholds (PPT), and reduce the effects of delayed onset muscle soreness (DOMS) in healthy individuals. Several researchers have documented positive post-exercise effects of RM for different sports, occupations, and fibromyalgia. 

**Range of motion.** The research does suggest that RM may increase joint ROM. Several researchers have demonstrated short-term post-intervention increases in joint ROM at the shoulder, lumbo-pelvis, hip, knee, and ankle. 

**Therapeutic intervention.** There is some evidence that suggests RM may have a positive impact on pain, joint ROM, and quality of life for individuals with fibromyalgia and myofascial pain syndrome. For sports and orthopedics, RM may have some benefits due to the possible neurophysiological effects (e.g. tissue relaxation and pain modulation) that occur to the local and surrounding tissues. Researchers have shown that RM to the agonist tissue may effect the muscle activity and PPT of the ipsilateral antagonist through reciprocal inhibition and the contralateral agonist through a crossover effect. This may have clinical implications in the presence of injury since rolling on the target or agonist tissues could create a desired neurophysiological effect to the injured antagonist or contralateral muscles. Further research is needed to confirm the therapeutic effects of this intervention. RM alone may not be sufficient enough to prevent or treat an injury.

When comparing the use of RM among rehabilitation professionals to what is found in the research, several similarities can be noted. A recent survey (June to August 2017) of 685 physical therapist Orthopedic and Sports Section members of the American Physical Therapy Association revealed the majority of professionals prescribe RM as an injury treatment (562/685, 82%) followed by a pre-exercise warm-up and post-exercise treatment (378/685, 55%), injury prevention (279/685, 41%), and for performance enhancement (215/685, 31%). It appears that rehabilitation professionals are using RM in similar ways that are found in the research. Part II of this series presents the complete survey results.

### PRECAUTIONS AND CONTRAINDICATIONS

To date, no clear evidence based safety guidelines have been reported for RM. The precautions and contraindications presented in this section reflect medical conditions that may be unsafe for a client.
The best available guidelines may be from related myofascial therapies. This section will synthesize evidence from the therapeutic massage literature which has existing best practice and safety guidelines. Prior to treatment, the professional is encouraged to conduct a thorough medical screening to determine if RM is safe for the client.

Before rehabilitation professionals prescribe RM to clients, they should consider potential precautions and contraindications and how the intervention is being administered. Three common ways of RM can be considered: self RM with bodyweight, self RM using the upper extremities, and assisted RM. Self RM using bodyweight, the client may lay or position a bodypart on a roller and apply pressure with their bodyweight and offset the weight with their hands and feet as needed. This type of RM might be an issue if the client cannot perform the movement due to a musculoskeletal impairment or other medical issue. Self RM with the upper extremity, the client may use a hand held RM device such as RM stick to massage a body region. This technique may require the client to have adequate upper extremity ROM, muscle strength, and endurance to perform the massage over a specific body region or for a certain amount of time. Assisted RM involves help from another person, such as a rehabilitation professional, that may use a hand held RM device to administer the massage. This technique requires effective communication between the professional and the client in order to grade the pressure, adjust the technique, and monitor the client’s perceived discomfort during the intervention.

These common RM techniques are not unique as other techniques may exist and may need to be individualized for each client. Regardless of technique, RM may require specific precautions or contraindications due to the mechanical pressure caused by the roller. Suggested precautions may include but are not limited to: hypertension, osteopenia, pregnancy, diabetes, varicose veins, bony prominences or regions, abnormal sensations (e.g. numbness), sensitivity to pressure, recent injury or surgery, inability to position body or perform RM, young children, older individuals, scoliosis or spinal deformity, and medications that may alter a client’s sensation (Table 1). Suggested contraindications are also presented in Table 2. It is important to note that some conditions such as but not limited to pregnancy, diabetes,

<table>
<thead>
<tr>
<th>Table 2. Roller Massage Contraindications.</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Skin rash, open wounds, blisters, local tissue inflammation, bruises, or tumors</td>
</tr>
<tr>
<td>• Osteoporosis</td>
</tr>
<tr>
<td>• Bone fracture or Myositis Ossificans</td>
</tr>
<tr>
<td>• Acute or severe cardiac, liver, or kidney disease</td>
</tr>
<tr>
<td>• Neurologic conditions resulting in loss or altered sensation (e.g. Multiple Sclerosis)</td>
</tr>
<tr>
<td>• Systemic conditions (e.g. Diabetes)</td>
</tr>
<tr>
<td>• Connective tissue disorders (e.g. Marfan syndrome)</td>
</tr>
<tr>
<td>• Medications that thin blood or alter sensations</td>
</tr>
<tr>
<td>• Chronic pain conditions (e.g. Rheumatoid Arthritis)</td>
</tr>
<tr>
<td>• Pregnancy (consult MD)</td>
</tr>
<tr>
<td>• Extreme discomfort felt by patient</td>
</tr>
<tr>
<td>• Deep Vein Thrombosis or Osteomyelitis</td>
</tr>
<tr>
<td>• Cancer or malignancy</td>
</tr>
<tr>
<td>• Hypertension (uncontrolled)</td>
</tr>
<tr>
<td>• Acute infection (viral or bacterial), fever, or contagious condition</td>
</tr>
<tr>
<td>• Bleeding disorders (e.g. Hemophilia)</td>
</tr>
<tr>
<td>• Recent surgery or injury</td>
</tr>
<tr>
<td>• Peripheral vascular insufficiency or disease</td>
</tr>
<tr>
<td>• Direct pressure over surgical site or hardware</td>
</tr>
<tr>
<td>• Direct pressure over face, eyes, arteries, veins (e.g. varicose veins), or nerves</td>
</tr>
<tr>
<td>• Direct pressure over bony prominences or regions (e.g. lumbar vertebrae)</td>
</tr>
<tr>
<td>• Severe scoliosis or spinal deformity</td>
</tr>
</tbody>
</table>
varicose veins, and hypertension can be considered either precautionary or contraindicative depending on the client. These conditions and others are listed in both categories.

The precautions and contraindications listed in this section are not all inclusive and should be considered a starting point for rehabilitation professionals to build their own list based upon their client population. Unfortunately, no consensus exists on this topic which required synthesis from the therapeutic massage literature which has existing guidelines. Future studies are needed to validate these suggested precautions and contraindications and to develop best practices and safety guidelines for RM.

**ASSESSMENT**

Trends in the use of clinical outcomes to measure the effects of RM by rehabilitation professionals has not been discussed in the literature. Researchers have used common patient reported outcomes (PROs) such as the numeric pain rating scale (NPRS) or visual analog scale in their studies. More specifically, the NPRS has been used to measure the post-treatment effects of RM on pain perception and to grade the pressure applied during RM testing by following a predetermined pain level. Researchers have also used objective measure such as joint ROM, PPT, vertical and broad jump, agility tests, movement based tests, sprints, maximum voluntary contraction, and isokinetic muscle strength (Table 1).

When comparing RM assessment techniques among professionals to what is used in the research, several similarities can be noted. The recently conducted survey revealed that the majority of professionals reported using PROs (549/685, 80%), and assessments for determination of effects of RM including joint ROM (404/685, 59%), movement-based testing (e.g. FMS™) (291/685, 42%), and pressure pain threshold testing (116/685, 17%). Rehabilitation professionals seem to be using similar clinical outcomes as reported in the research. Interestingly, approximately 7% (51/685) of respondents reported not measuring the post-treatment effects of RM. The complete results of the survey will be presented in Part II of this clinical commentary series.

**CLINICAL IMPLICATIONS**

This discussion attempts to provide a framework for the development of clinical standards for describing RM, indications, precautions, contraindications, and assessment. There are many unknowns regarding RM which warrant such a discussion to help establish best practice standards and to accurately disseminate the information to clients.

For describing RM, a working description that evolves as the knowledge grows may be the best strategy to differentiate RM from other myofascial therapies. For indications, RM can be used as a warm-up, post-exercise recovery, and to increase joint ROM. RM may also have therapeutic benefits for individuals with fibromyalgia and myofascial pain syndrome. The list of indications should constantly evolve as clinicians and researchers further learn the utility of the intervention. The precautions and contraindications discussed may seem intuitive to rehabilitation professionals but may not be fully understood by clients. General safety guidelines for RM may help clients use the devices properly and reduce the risk of injury. Due to the lack of existing guidelines, the suggestions were synthesized from other myofascial therapies which may offer the best evidence at this time. As far as assessment, proper assessment of outcomes after RM is necessary to determine its effects on clients. It appears that rehabilitation professionals are using similar PROs and objective measures such as joint ROM, movement based testing, and PPT as noted in the research.

**CONCLUSIONS**

Part I of this clinical commentary series provides a discussion on proposed clinical standards such as describing RM, indications, precautions, contraindications, and assessment. To date, these standards have not been discussed in the literature. The goal of Part I is to be the starting point to encourage further development of these standards. Rehabilitation professionals and researchers are encouraged to build upon the existing information and help further develop best practice standards for RM.

**REFERENCES**


