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ABSTRACT
Pathology of the long head of the biceps brachii tendon (LHBT) is a common source of shoulder pain. While a careful history and a thorough physical examination are important steps in the assessment of LHBT pathology, it is still difficult to differentiate the type and severity of the pathology. Currently, the gold standard for confirming a diagnosis of LHBT pathologies is arthroscopic examination. Additionally, MRI is commonly ordered for diagnosis. Since an accurate diagnosis of pathology is critical for treatment success, musculoskeletal ultrasound (MSK US) is an attractive adjunct to the diagnostic process due to it being safe, inexpensive and non-invasive. When used in combination with clinical special tests, MSK US can drastically increase the diagnostic accuracy of the clinical examination.

INTRODUCTION
Disorders of the long head of the biceps brachii tendon (LHBT) are a commonly recognized source of shoulder pain.\textsuperscript{1–5} It is not unusual to have LHBT pathology associated with rotator cuff tears and subacromial impingement.\textsuperscript{6–7} Rotator cuff deficiency increases superior translation of the humeral head in relation to the glenoid fossa, causing the LHBT, a humeral head depressor, to be subject to overuse injury. Clinical success is always predicated upon an accurate diagnosis and understanding of the pathological process. While a careful history and a thorough physical examination are important steps in the assessment of LHBT pathology, it is still difficult to differentiate the type and severity of the pathology. MSK US imaging has become an established tool to assist in and optimize the diagnostic process. While MSK US is very accurate in the diagnosis of rotator cuff tears, there is moderate to strong evidence to support the use of MSK US in diagnosis of LHBT pathology.\textsuperscript{8} MSK US can accurately help to diagnose partial and full-thickness tears, LHBT subluxation/dislocation, and long head biceps (LHB) tendinopathy.\textsuperscript{9}

At times, MSK US can be a difficult diagnostic tool to use clinically and interpret the results. However, when used correctly, MSK US is a valuable tool to accurately diagnose a variety of LHBT pathologies. Therefore, its use should help to facilitate diagnosis and treatment of patients with shoulder pain due to suspected biceps tendon pathologies. The goal of this article is to provide a few tips and tricks to assist in using MSK US as a diagnostic tool for the assessment of the LHBT.

PATIENT POSITION

\textbf{Figure 1a (left):} Patient is seated with shoulder and elbow relaxed. Shoulder at 0 degrees of abduction, neutral rotation, elbow flexed and resting on leg or pillow with forearm supinated.

\textbf{Transducer Placement:} Short Axis (SAX). Probe placed transversely on the proximal anterior aspect of the shoulder, over the LHBT.

\textbf{Figure 1b (right):} Patient is seated with shoulder and elbow relaxed. Shoulder at 0 degrees of abduction, neutral rotation, elbow flexed and resting on leg or pillow with forearm supinated.

\textbf{Transducer Placement:} Long Axis View (LAX). Probe placed longitudinally on the proximal anterior aspect of the shoulder, over the LHBT.
NORMAL TENDON

Figure 2a: Normal Tendon-Short Axis View
LHBT is located deep within the inter-tubercular groove and viewed as a bright hyperechoic defined tendon. It is easily seen see between the bony greater and lesser tubercles. The thin band of bright tissue overlying the top of the bicep's tendon is the transverse humeral ligament.

Figure 2b: Normal Tendon-Long Axis View
LHBT is seen running parallel along the image running proximal to distal from left to right. It should be seen as a bright hyperechoic fibrous band of tissue. The deltoid is seen above as a linear tissue with darker muscle bundles.

LHB TENDON PATHOLOGY

Figure 3a: Effusion and edema are seen as an area of hypoechoic signal within the tendon sheath surrounding the LHBT. The anechoic ring is known as a “halo sign” on a SAX view. This edema could be either a tenosynovitis or a capsulitis. The LAX will be the differential view.

Figure 3b: Joint effusion within the tendon sheath seen here on the LAX. On the LAX views, it reveals presence of fluid distally indicating a tenosynovitis. A capsulitis would not show effusion in the biceps tendon sheath distally on the LAX view.
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The Use of the Internal Brace to Repair the UCL Injury of the Elbow in Athletes

Kevin E Wilk, PT, DPT, FAPTA, Zachary M Thomas, PT, DPT, OCS, CSCS, Christopher A. Arrigo, MS, PT, ATC, Ashley M Campbell, PT, DPT, PCS, Amir Shahien, MD, Jeffrey R Dugas, MD

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Keywords: UCL, elbow, UCL repair

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The number of injuries to the ulnar collateral ligament (UCL) of the elbow are rising every year. Several studies have reported increasing numbers of injuries, associated surgeries, and that patients affected by UCL pathology are gradually becoming younger. Hodgins et al reported a 195% increase in the number of UCL surgeries in the state of New York from 2002 to 2011.1 Erickson et al reported the age range for most UCL surgeries in the United States to be between 15-19.2 Conte et al noted in a survey of professional baseball teams, that 25% of all major league pitchers have undergone UCL surgery, while only 14% of minor league pitchers have had UCL operations.3 Just four years later, the number of minor league pitches reporting prior UCL surgery increased by 5% to 19% and the number of major league pitchers affected to 26%.4

The American Sports Medicine Institute (Birmingham, AL) has noted a shift in the majority of patients presenting with UCL injuries. Twenty-five years ago, that majority were college and professional aged baseball players, now the athletes sustaining UCL injuries are predominately younger than collegiate age. From 2001 to 2019 at the Andrews Sports Medicine and Orthopaedic Center 4,606 UCL surgeries were performed with an average age of 17.6 years. This shift to younger patients being affected by UCL injury more often brought into focus the dilemma of athletes nearing the end of promising careers almost before they have even started. This also demonstrates the importance and the need to return to play as soon as safely possible. The internal brace repair for the UCL injured athlete appears to be a reasonable option to address these issues for the appropriate candidate.

Diagnosis of UCL tears is accomplished through a combination of physical exam and diagnostic imaging, in the context of patient history.5 Non-operative management of UCL injury has historically been reserved for low to medium-grade partial tears.6 Non-operative treatment is comprised of rest from throwing, rehabilitation to strengthen and improve throwing mechanics, and a graduated return to throwing program over a 3-4 month period of time. Additionally, the use of biologics such as platelet rich plasma (PRP) have the potential to augment the effectiveness of non-operative management in certain instances.7 For high demand throwing athletes that fail conservative management, surgical intervention is warranted.

Since Dr. Frank Jobe’s initial description of the UCL reconstruction in 1974, it has been the gold standard for treatment of medial sided elbow pain and laxity in the throwing athlete.8,9 Reconstruction techniques have evolved over time with varied applications including docking, Jobe, and modified-Jobe techniques.10-12 Early comparisons of repair versus reconstruction revealed poor outcomes, with less than 30% of repairs returning to the same or higher level of play, especially in a subset of Major League Baseball (MLB) overhead athletes.13,14 Although return to play rates are high with UCL reconstruction, between 85 -90%, the rehabilitation process which ranges between 12-18 months for pitchers is longer than desired.15

Newer technology and greater experience performing direct repairs of the UCL have demonstrated return to play outcomes greater than 95%.16,17 Dugas et. al published two outcome studies first establishing the non-inferiority of UCL repair with internal brace to the modified Jobe reconstruction and then reporting outcomes and return to play to the same or higher level in greater than 90% of patients, 92% of which returned to competition in a 6-7 month time frame.18,19

Although the potential for shorter rehabilitation and quicker return to play are attractive advantages of UCL repair with internal brace when compared with a reconstruction, patient selection is crucial for success. There has been a trend toward an increasing number of adolescent and youth sport participants with UCL injury.16,17 These younger athletes typically have end-avulsions of the UCL or partial tears of the ligament in otherwise healthy ligament tissue. These types of injuries lend themselves well to repair with internal brace. The UCL repair cannot augment a
preexisting tissue deficiency. Patients with chronic UCL insufficiency or adaptive changes such as ossification of the ligament are not repair candidates.

SURGERY TECHNIQUE

The authors’ current surgical approach to repair of the UCL includes the standard medial incision just posterior to the medial epicondyle (Figure 1). The cubital tunnel is exposed, and the ulnar nerve is dissected out both proximally and distally. The ulnar nerve is transposed to decrease the rate of post-operative ulnar neuritis. The sublime tubercle and medial epicondyle are then identified. For UCL exposure, a muscle-elevating approach is used to elevate the flexor-pronator musculature off the anterior band of the UCL. With full exposure of the ligament, the anterior band is split in line with its fibers in order to access and debride a proximal or distal avulsion. Once completed the internal brace, which was prepped on the back table, is placed through a 3.5 mm SwiveLock (Arthrex Inc, Naples, FL) with a 2-0 nonabsorbable suture for repair.

The drill guide is then inserted either on the center of origin of the UCL at the medial epicondyle for proximal tears or the anterior aspect of the sublime tubercle for distal tears. The first anchor of the internal brace is placed appropriately and the limbs of the nonabsorbable suture are passed through the ligament’s anterior and posterior bands and tied in simple fashion to complete the repair. The remaining FiberTape (Arthrex Inc, Naples, FL) is then loaded through a second 3.5 mm SwiveLock. A similar drilling and taping process is performed on either the remaining proximal or distal end of the ligament. The longitudinal split in the ligament is then closed with an interrupted 0 vicryl. The FiberTape is tensioned as to not supersede the native tension of the ligament and the anchor is provisionally inserted as the arm is taken through a full range of motion to confirm reduction of the joint with adequate tensioning and isometry on the graft, ensuring there is no non-physiologic constraint of the repaired UCL. The 3.5 SwiveLock is then inserted until the anchor is seated. Finally, interrupted 0 vicryl sutures are placed around the native ligament and around the internal brace to supplement fixation and prevent windshield wiperining of the brace itself (Figure 2). The ulnar nerve is transposed anteriorly and secured under two fascial slings with 3-0 vicryl and the internal brace is complete (Figure 3a/b).

Surgical video

In a cadaver study examining the UCL repair construct, UCL repair with internal bracing is more resistant to gap formation under fatigue loading than UCL reconstruction. Additionally, in cadaver specimens, contact mechanics of reconstructed and repaired specimens were not significantly different. Both reconstruction and repair procedures returned the overall resistance of the joint to valgus torsion to near-intact levels. Clinically, the authors have experienced good outcomes utilizing the described technique for UCL repair with Collagen-Dipped FiberTape augmentation in Overhead-Throwing Athletes.

REHABILITATION

Rehabilitation following a UCL repair with internal brace begins on post-operative day 1 with an emphasis on shoulder and wrist passive range of motion (PROM), light voluntary muscle activation exercises for the shoulder, dressing/wound care, and ensuring that there is optimal communication between the rehabilitation team and ath-
The goal of the rehabilitation process is to return the athlete to his or her previous functional level, or better, as quickly and safely as possible. Phase one (week 1) is intended to protect healing tissue, reduce pain and inflammation, minimize muscular atrophy, and regain full wrist/shoulder motion, while allowing early healing of the surgical repair. For the first week after surgery, the patient is placed in an adjustable ROM elbow brace (Figure 4), with the elbow immobilized at 90° of flexion to protect the healing of the UCL repair and ulnar nerve transposition. A primary focus in phase one is on voluntary muscle activation to help minimize muscular atrophy of the shoulder and scapulothoracic musculature, with all exercises performed isometrically, in a non-painful submaximal fashion with the elbow brace locked at 90° of flexion. Rhythmic stabilization drills are also performed for the shoulder external and internal rotator muscles to begin re-establishing proprioception and neuromuscular control of the upper extremity.

Phase two (weeks 2-5) focuses on gradually restoring elbow joint ROM (Figure 5), improving muscular strength and endurance, and normalizing joint arthrokinematics. On day 8 post-surgery, the elbow ROM brace is set to allow elbow motion from 30° to 110° of flexion. At the beginning of week 3 the brace is unlocked further progressing to 10° to 125° of motion. At this time the Throwers Ten program is usually initiated (Figure 6), based on the patient’s progression and signs and symptoms (Appendix A). By week 4 the elbow brace is unlocked to allow 0° to 145° of motion. Full elbow ROM is expected by the end of post-operative week 4.

Phase three (6-8 weeks) of the rehabilitation process emphasizes maintaining (or fully restoring, if still limited) elbow and upper extremity mobility, improving muscular strength and endurance, reestablishing neuromuscular control of the elbow complex, and continuing with the progression of functional activity. During this phase, 2-hand plyometric upper extremity exercises are initiated, beginning with two hand plyometric chest pass (Figure 8). One hand plyometric throwing into a wall or rebounder with a light plyometric ball (1 & 2 pounds) is initiated at 8-10 weeks (Figure 9), depending on the patients progress and assessment. Dynamic stabilization drills such as ball on wall with stabilization (Figure 10), and one hand ball throws into the wall with end range stabilization (Figure 11) are also routinely performed in this timeframe.

Phase four begins at week 9 and goes through week 16 following surgery. The goal of this phase is to gradually

*Figure 3b. UCL internal brace in place.*

*Figure 4. Elbow locked at 90° in adjustable elbow fixation brace 1 week post-operatively.*

*Figure 5. Passive range of motion following UCL surgery.*
increase strength, power, endurance, and neuromuscular control to prepare the athlete for a gradual, progressive return to sports. The athletes exercise program is progressed to include more aggressive eccentric and plyometric movements during this phase. An interval hitting program is initiated at week 10, while an interval throwing program (ITP) for the overhead athlete is allowed to begin at week 12 after surgery, if the athlete is ready. In most cases, pitchers will progress to throwing from a mound approximately 8 to 10 weeks after initiation of an ITP.
The final phase (16+ weeks) of the rehabilitation process is the return-to-activity phase. During this phase, the goal is to allow the athlete to progressively return to full activity and competitive throwing. Gradual return to competitive throwing begins 5 months following UCL repair with internal brace, in contrast to 9 to 12 months following UCL reconstruction.\(^\text{15,29}\) During this return to competition phase, the athlete is instructed to continue the throwers ten +4 program to maintain ROM and strength for the entire body (Appendix A).

The outcomes demonstrated thus far using this procedure and rehabilitation program have been encouraging. UCL repair with internal brace has been performed at our center since 2013 with approximately 527 procedures performed to date. Dugas et al examined outcomes in 111 overhead athletes, 92% (102/111) of those who desired to return to the same or higher level of competition were able to do so at a mean time of 6.7 months.\(^\text{19}\) Recently, Rothermich et al presented results of 40 non-throwing athletes who had undergone UCL repair with a minimum follow up of 2 years, the results indicated a 95% return to play rate with the average time to play occurring at 7.4 months.\(^\text{30}\) Based on our clinical observations, the success rate of 92-95% appear to be sustained for the long term (5-7 years and beyond).

**SUMMARY**

The UCL is frequently injured in overhead athletes and these injuries continue to increase in number, particularly in youth athletes. Surgical repair of the UCL with internal brace is a viable option in athletes who meet specific find-
ings at the time of surgery. The rehabilitation of this unique surgical procedure has been presented based on the authors’ experience treating more than 350 athletes over the past 5 years. The average time required for an athlete to return to participation in this cohort is 7 months which is approximately 5 months less than average return to play times after UCL reconstruction surgery. Long-term results of this surgery and rehabilitation program are still needed but the initial experience is extremely promising. Long term studies are needed to determine the effectiveness and longevity of this procedure and rehabilitation program.

Submitted: September 01, 2022 CST, Accepted: October 22, 2022 CST
Table 1. UCL Repair with Internal Brace Rehabilitation Program

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<th>Long Term Goals:</th>
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<tr>
<td>• Full Elbow, Wrist, Shoulder Range of Motion Week 6</td>
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<td>• Pain free ROM UE</td>
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<td>• Performing Shoulder, Arm &amp; Entire Body Strengthening Program</td>
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<tr>
<td>• Improving Entire Body Strength &amp; Flexibility</td>
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<tr>
<td>• Return to Unrestricted Throwing</td>
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I. Initial Phase: (Week 1)

Goals: Full wrist ROM  
Decrease swelling  
Decrease pain  
Prevent muscle atrophy

| Day of Surgery | 1. ROM Brace locked at 70 degrees to Elbow Joint for 7 days  
2. PROM wrist & hand |
|----------------|---------------------------------------------------|
| Post op Day 1 and 2 | 1. Locked ROM Brace at 70 degrees flexion for 7 days  
2. Immediate post-op hand, wrist, and hand exercises  
a. Putty/grip strengthening  
b. Wrist flexor stretching  
c. Wrist extensor stretching  
d. Shoulder PROM – all directions  
e. Pendulum exercises |
| Post-op Day 3 through 7 | 1. PROM shoulder & wrist/hand  
a. ER/IR PROM exercises  
b. Shoulder flexion to tolerance  
c. Active scapular protraction/retraction & elev/depress seated in brace  
2. Continue above exercises  
a. Shoulder isometrics  
1. ER & IR  
2. Abduction, Flexion & extension  
b. Scapular strengthening (seated NM control drills with manual resistance)  
c. Hand gripping exercises |

II. Acute Phase (Week 2-4)

Goals: Gradually restore Elbow Joint ROM  
Improve muscular strength and endurance  
Normalize joint arthrokinematics

| Week 2, Day 8: Begin PROM & AAROM Elbow ROM 30-110°  
Progress to Elbow ROM brace (30-110°)  
Elbow AAROM/PROM exercises | 1. Initiate AROM elbow  
2. Initiate AROM shoulder joint  
3. Scapular strengthening exercises  
4. Progress to light isotonic strengthening at day 10 |
| Beginning Week 3: Progress Elbow ROM to 10-125° | 1. Initiate Thrower's Ten Exercise Program (day 15) |

III. Intermediate Phase: (Week 4-8)

Goals: Restore full Elbow ROM  
Progress UE strength  
Continue with functional progression

| Week 4-6: Progress Elbow ROM to 0-145° | 1. Progress to Advanced Thrower’s Ten Program  
2. Progress elbow & wrist strengthening exercises  
4. Wrist & Forearm strengthening – dumbbell |
| Beginning Week 7: Discontinue brace at end of week 6  
Initiate 2 hand plyometric throws  
Prone planks  
Side plank on uninvolved side & ER on throwing side |

The Use of the Internal Brace to Repair the UCL Injury of the Elbow in Athletes
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<th>Long Term Goals:</th>
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<tr>
<td><strong>Week 8:</strong> Continue with advanced thrower’s ten program Side planks with ER strengthening</td>
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<th>IV. Advanced Phase: (Weeks 9-14)</th>
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<tr>
<td><em>Criteria to progress to Advanced Phase:</em></td>
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<tr>
<td>1. Full nonpainful ROM</td>
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<td>2. No pain or tenderness</td>
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<td>3. Isokinetic test that fulfills criteria to throw</td>
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<td>4. Satisfactory clinical exam</td>
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<tr>
<td>5. Completion of rehab phases without difficulty</td>
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<tr>
<th>Goals: Advanced strengthening exercises</th>
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<tr>
<td>Initiate Interval Throwing Program</td>
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<tr>
<td>Gradual return to throwing</td>
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<tr>
<th>Beginning Week 9:</th>
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<tr>
<td>Continue all strengthening exercises</td>
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<tr>
<td>Initiate 1 hand plyometric throws</td>
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<tr>
<td>Advanced thrower’s ten program</td>
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<tr>
<td>Plyometrics program (1 &amp; 2 hand program)</td>
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<th>Beginning Week 10:</th>
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<tr>
<td>Seated machine bench press</td>
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<tr>
<td>Initiate Interval Hitting Program (week10)</td>
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<tr>
<td>Seated rowing machine</td>
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<tr>
<td>Progress Biceps (dumbbell) strengthening</td>
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<tr>
<td>Progress Triceps pushdowns</td>
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<tr>
<th>Beginning Week 11-16:</th>
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<tr>
<td>Begin Interval Throwing program phase 12 (Long toss program) Phase I Continue all exercises as in week 9 - 10</td>
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<th>Beginning Week 16-20:</th>
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<tr>
<td>Initiate Interval Throwing Program Phase II (Off mound program)</td>
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<td>Initiate mound throwing when athlete is ready &amp; completed ITP Phase I</td>
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<tr>
<td>-Continue Advanced Thrower 10 exercise program</td>
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<tr>
<td>-Continue plyometrics</td>
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<tr>
<td>-Continue ROM &amp; Stretching programs</td>
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<th>V. Return to Play Phase: (weeks 20+):</th>
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<tr>
<td><strong>Goal:</strong> Gradual return to competitive throwing</td>
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<tr>
<td>Continue all exercises &amp; stretches</td>
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<tr>
<th>Week 20-24+:</th>
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<tr>
<td>Initiate gradual return to competitive throwing</td>
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<tr>
<td>Perform dynamic warm-ups &amp; stretches</td>
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<tr>
<td>Continue thrower’s ten program</td>
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<tr>
<td>Return to competition when athlete is ready (Physician Decision)</td>
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Note: ** Each athlete may progress thru ITP at different rates/pace. Should complete 0-90 ft within 3 weeks of starting it & complete 120 ft within 8 weeks then begin mound program.
REFERENCES


SUPPLEMENTARY MATERIALS

Appendix A - Throwers Ten

Appendix B - Advanced throwers ten
Systematic Review/Meta-Analysis

The Efficacy of the Mulligan Concept to Treat Meniscal Pathology: A Systematic Review

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Keywords: lesion, manual therapy intervention, Mobilization with Movement (MWM), rehabilitation, knee injury

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Background
Meniscal pathologies are common knee injuries and arthroscopic surgery is the current accepted gold standard for treatment. However, there is evidence to support the use of the Mulligan Concept (MC) Mobilization with Movement (MWM) for meniscal pathologies including the 'Squeeze' technique, tibial internal rotation (IR), and tibial external rotation (ER).

Hypothesis/Purpose
The purpose of this systematic review was to critically appraise the literature to investigate the effectiveness of MC MWMs for meniscal injuries on patient reported pain, function, and multi-dimensional health status in patients with clinically diagnosed meniscal pathologies.

Study Design
Systematic Review

Methods
A literature search was completed across multiple databases using combinations of the words "knee, function, mobilization with movement, MWM, mulligan concept, MC, meniscal pathology, meniscal derangement, and meniscal tear." Studies written within the prior 10 years that examined MC MWM techniques to treat knee meniscal injury were included. Articles that met the inclusion criteria (used MC MWM 'Squeeze' technique, tibial IR, or tibial ER for treatment of clinically diagnosed meniscal pathologies; Patient reported outcome [PRO] measures had to be used in the assessment of knee pain or function) were analyzed for quality. Randomized control trials were analyzed using the PEDro scale and the Downs & Black (D&B) checklist, case series were analyzed using the Joanna Briggs Institute (JBI) checklist, and case reports were analyzed using the CARES checklist.

Results
Six articles met the inclusion criteria and were included in this review, two randomized controlled studies, two case series, and two case reports consisting of 72 subjects. All six papers included reports of improvements in pain and function that were either...
statistically significant or met the minimal clinically important difference (MCID). Five studies reported the Disablement in the Physically Active (DPA) scale that also demonstrated statistically significant differences or met the MCID. The MC MWM 'squeeze' technique, tibial IR, or tibial ER demonstrated the ability to reduce pain, improve function, and improve patient perceived disability following treatment of a clinically diagnosed meniscal pathology. These studies demonstrated short term results lasting from one week to 21 weeks.

**Conclusion**

Treatment interventions incorporating MC MWM techniques demonstrated reduction of pain and improvement in function in the short term in patients with clinically diagnosed meniscal pathologies.

**Level of Evidence**

2a

**INTRODUCTION**

Meniscal injuries are diagnosed through clinical evaluation, magnetic resonance imaging (MRI), or diagnostic arthroscopy. Arthroscopy, which is reported to have an accuracy of 90-95% and has the benefit of immediate surgical correction being able to be performed, is considered the gold standard diagnostic technique; however, arthroscopy has drawbacks such as unnecessary surgical costs and risks. The reported diagnostic accuracy of MRI has been as high as 88%, but MRI also has drawbacks, such as high prevalence of findings in asymptomatic uninjured knees, increased healthcare costs, and challenges with accessing imaging. Thus, accurate diagnosis with a physical exam is valuable; comprehensive physical examination and testing batteries (i.e., positive McMurray's, Thessaly's, and Aphey's tests) have been associated with high diagnostic accuracies of 90% and 81%, respectively. Similarly, a clinical prediction rule of a history of catching or locking, pain with forced hyperextension, pain with maximum knee flexion, joint line tenderness, and pain or clicking while performing McMurry's test has been reported to have a positive predictive value of 92.3% and a positive likelihood ratio of 11.45 when all five signs are present in a clinical exam.

Once diagnosed, meniscal injuries are often treated surgically in combination with conservative therapy or after conservative therapy has failed to produce the desired improvement. In fact, arthroscopic partial meniscectomy (APM), which addresses meniscal injury by removing the damaged meniscal tissue, is one of the most commonly performed orthopedic surgeries. Surgical approaches, however, have often failed to have the desired result. For example, APM has not been found to outperform sham surgery or conservative management, and surgery has resulted in patients who were more susceptible to developing osteoarthritis. Arthroscopic repair, which has a reputation as the "gold standard" for meniscal injuries in cases where it is feasible to repair the specific meniscal tear present, has high rates of failure (e.g., patients often redevelop symptoms, patients require additional corrective operations, etc.). When patient history, physical examination, current pain, and dysfunction or mechanical symptoms indicate meniscal injury, non-operative or conservative treatment is recommended.

Thus, there is a need to consider other treatment options for patients who present with the signs and symptoms of a meniscal pathology due to the prevalence of meniscal injuries, potential undesired surgical outcomes (e.g., adverse long-term outcomes), and recommendations for conservative care. The Mulligan Concept (MC), introduced by Brian Mulligan, is an innovative conservative treatment approach used to address common issues (e.g., joint pain, decreased ROM, movement dysfunction, etc.) associated with knee joint pathology. The MC incorporates movement with mobilization by combining the patient's active range of motion (AROM) with a clinician's joint glides to attempt to produce immediate changes in the patient's complaints and impairment measures. While consensus on the mechanism of action has not been reached, application of the MC is thought to alter the mechanoreceptive and nociceptive responses to promote immediate improvements in the patient's impairment.

Specific MC mobilizations with movement (MWMs) techniques have been proposed as effective conservative non-surgical interventions for meniscal pathology. Researchers have recently begun to examine the effects of the proposed MC MWM techniques (i.e., 'squeeze' technique, tibial IR, and tibial ER) in patients with clinically diagnosed meniscal lesions. A synthesis of the available literature to assess the effectiveness of the proposed meniscal MC MWM techniques in the treatment of clinically diagnosed meniscal lesions has not been conducted. Examining the effects of these MC MWMs in clinically diagnosed meniscal lesions would provide an update on the evidence and help inform practitioners on an evidence-based method for incorporating MC MWMs 'squeeze', tibial IR, and tibial ER into clinical practice. Therefore, the purpose of this systematic review was to critically appraise the literature to investigate the effectiveness of MC MWMs for meniscal lesions on patient reported pain, function, and multi-dimensional health status in patients with clinically diagnosed meniscal pathologies.
METHODS

STUDY DESIGN

The systematic review was registered on the International Prospective Register of Systematic Reviews (PROSPERO), a database for tracking the quality of systematic reviews in health professions (CRD42021278025). The 13-item PROSPERO checklist for the creation of systematic reviews was followed for accuracy of study design and reporting. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 27 item checklist was also used in the creation of the systematic review to ensure the quality of the study design.

SEARCH STRATEGY

An electronic search of the literature was conducted in May 2022. The following databases were used for the literature search: PubMed, SportDiscus, CINHAL, MEDLINE, the University of Idaho library, and the indexed reference of published works listed on the Mulligan Concept website. The search was limited to the last ten years with an additional filter to specify academic articles or journal articles depending on the database. The search terms used were "menisc* AND mulligan AND pain". Other search terms (i.e., knee, function, mobilization with movement, MWM, mulligan concept, MC, meniscal pathology, meniscal derangement, and meniscal tear) were used to find additional studies, but no additional studies were identified with these terms. A hand search of the references of identified articles was also performed; however, no additional studies were identified with this process, while one additional study was identified on the Mulligan Concept website that was published in the Journal of Sports Medicine and Allied Health Sciences, which is the official journal of the Ohio Athletic Trainers Association.

ELIGIBILITY CRITERIA

Each study had to meet the following inclusion criteria to be eligible for this review. A clinical diagnosis of a meniscal pathology consisting of a minimum of three of the following items during the physical exam: 1) a positive test for McMurray's, Thessaly's, or Apley's Compression tests; 2) pain at end range of knee flexion; 3) pain at end range of knee extension; 4) joint line tenderness; and 5) a history of painful popping or clicking. Additionally, the use of the MC MWM 'squeeze' technique, tibial IR, or tibial ER for treatment of clinically diagnosed meniscal pathologies had to be present. Finally, PRO measures had to be used in the assessment of knee pain or function. Studies were excluded if a non-MWM MC technique or alternative forms of manual therapy were utilized or if the included participants had any other clinically diagnosed knee pathology, hyperalgesia, or a previous history of knee surgery. Studies were also excluded if they were not published in English, not published within the last 10 years, or did not meet the expectations for blinded peer-review (e.g., dissertations, poster presentations,).

STUDY SELECTION

One author (NR) conducted the initial search, while a second author (SL) repeated the search to ensure the accuracy and repeatability of the search results. The two search authors (NR and SL) were blinded to the initial review of titles and abstracts and met to ensure final inclusion was consistent. Four of the authors (NR, SL, RH, and DB) independently completed a full text review of the studies that met inclusion and exclusion criteria and met to reach consensus for inclusion; a fifth author (RB) was consulted to confirm inclusion in the event of an impasse. All the authors agreed that the studies selected met the criteria for inclusion after review.

DATA COLLECTED

The studies included were graded with the following scales to assess and measure the study quality (e.g., study type, internal validity, level of evidence, PRISMA). The PEDro scale was used to assess the internal validity of the randomized control trials (RCTs); scores of seven or higher were considered high methodological quality, five to six were fair quality, and zero to four were poor quality. The Downs and Black (D&B) Checklist for randomized studies examining health care interventions was also utilized to evaluate included RCTs. The 27 item D&B Checklist was scored out of 32 total points where ranges of corresponding scores were given: excellent (26-32); good (20-25); fair (15-19); and poor (< 14). Any identified case series was assessed with the Joanna Briggs Institute (JBI) checklist for case series. A 6/10 or greater indicated a low risk of bias. Identified case studies were assessed with the CARES checklist and were scored out of twelve. The CARES checklist was scored on a 0-12 scale by giving a point to any question within a category when answered "yes" by the reviewer. The last question (Question 13) was not scored because it is intended for the completion of a case study by the original author and is not always reported in the study. Each study was assigned a level of evidence in accordance with the Oxford Center of Evidence-Based Medicine. This system of assessment was designed to quickly assess the best literature based on the study's design. Each study design falls within a specific level that can be graded up or down based on the quality of the study.

DATA EXTRACTION

The total number of participants and general demographic information were extracted from each qualified study. The primary data extracted from each article were study characteristics (e.g., publication data, study design, etc.), methodology (e.g., treatment protocol, inclusion/exclusion criteria, etc.), and results. Patient reported pain was assessed by the Numeric Pain Rating Scale (NRS). Patient-reported function was assessed by the Patient-Specific Functional Scale (PSFS), while multi-dimensional (e.g., impairment, quality of life, etc.) patient-reported assessment of health status was assessed with the Disabillity in the Physically Active (DPA) and Knee Osteoarthritis Outcome Score (KOOS). The
Figure 1. PRISMA flow diagram
Table 1. Study Participants

<table>
<thead>
<tr>
<th>Study</th>
<th>Participant Demographics</th>
<th>Clinical Diagnosis of Meniscal Pathology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasturi (2020)²⁸</td>
<td>N=40 (32M, 8F) Control (N=20) Intervention (N=20) Average age of all participants 28.87y (SD 7.09)</td>
<td>Each participant had all the following findings:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Joint line tenderness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Restricted AROM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with terminal knee flexion, knee extension, and internal/external rotation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Feeling of locking and instability in the knee joint</td>
</tr>
<tr>
<td>Hudson (2018)²¹</td>
<td>N=23 (11M, 12F) Both athletic and general populations Age range: 14-62 y Average Age 24.91y (SD 12.09) Control (N=11) Acute: 3</td>
<td>Inclusion: Participants presented with at least three of the following findings:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Chronic: 8 Intervention (N=12) Acute: 6 Chronic: 6 Generally healthy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Positive McMurray’s test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with maximal knee flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with maximal knee extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Joint line tenderness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• History of clicking and/or popping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive finding on at least one of the following rotational tests:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Apley’s compression and distraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Thessaly’s at 20°</td>
</tr>
<tr>
<td>Sanchez (2017)²⁴</td>
<td>N=1 26-year-old physically active female</td>
<td>• Insidious right knee stiffness and swelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• History of locking and popping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with terminal knee extension and flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Positive Thessaly’s test at 5° and 20° of knee flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Positive Apley’s compression test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Joint line tenderness</td>
</tr>
<tr>
<td>Hudson (2016)²⁷</td>
<td>N=5 (4M, 1F) All acute meniscal injury Age range: 15-24 years Average age: 19.6 (SD 3.2)</td>
<td>Inclusion: Participants presented with at least three of the following:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Positive McMurray’s test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with terminal knee flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with terminal knee extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Joint line tenderness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• History of clicking and/or popping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive finding on at least one of the following rotational tests:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Apley’s compression and distraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Thessaly’s at 20°</td>
</tr>
<tr>
<td>Brody (2015)²⁶</td>
<td>N=2 (1M, 1F) Healthy college students and recreational athletes</td>
<td>Inclusion:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Joint line knee pain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• History of catching or locking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with knee flexion or extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive finding on at least one or more of the following orthopedic special tests:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• McMurray</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Apley’s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Thessaly</td>
</tr>
<tr>
<td>Rhinehart (2015)²⁹</td>
<td>N=1F 20-year-old female soccer player DX: lateral meniscus pathology</td>
<td>Clinical diagnosis of meniscal pathology due to the following examination findings:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Inability to fully flex or extend knee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain with stairs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Sporadic giving out of knee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Joint line tenderness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Positive McMurray and Thessaly test for pain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Moderate swelling at both medial and lateral joint lines</td>
</tr>
</tbody>
</table>

M-Male; F- Female; y – years; SD-Standard Deviation; DX-diagnosis; AROM-active range of motion

Lower Extremity Functional Scale (LEFS), Global Rating of Change (GRoC), Range of motion (ROM), and Client Specific Impairment Measures (CSIM) were assessed as secondary outcomes when reported. Lastly, follow-up results were collected to determine the long-term effectiveness of the treatment intervention.

Primary Outcomes

Pain

The NRS is an outcome measure designed to assess pain intensity. All six studies utilized the NRS, which is a single-item measure that ranges from 0 (no pain) to 10 (most severe pain) and is used to assess the best, current, and worst pain the patient has experienced over the past...
Table 2. Characteristics of Included Studies

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Study Design</th>
<th>Participants</th>
<th>Intervention</th>
<th>Comparison</th>
<th>Outcome Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasturi (2020)28</td>
<td>Experimental Randomized Control Trial</td>
<td>N=40 (32M, 8F) Control (N=20) Intervention (N=20)</td>
<td>MC 'squeeze' technique along with conventional therapy</td>
<td>Conventional Therapy</td>
<td>NRS PSFS Knee ROM</td>
</tr>
<tr>
<td>Hudson (2018)21</td>
<td>Experimental Randomized Control Trial</td>
<td>N=23 (11M, 12F) Control (N=11) Intervention (N=12)</td>
<td>Mulligan with Movement 'squeeze' technique</td>
<td>Sham Mulligan Treatment</td>
<td>NRS PSFS DPA KOOS</td>
</tr>
<tr>
<td>Sanchez (2017)24</td>
<td>Case Study</td>
<td>N=1F</td>
<td>Tibial IR Mobilization with Movement And MC 'squeeze' technique</td>
<td>None</td>
<td>DPA PSFS NRS</td>
</tr>
<tr>
<td>Hudson (2016)27</td>
<td>Case Series</td>
<td>N=5 (4M, 1F)</td>
<td>MC 'squeeze' technique</td>
<td>None</td>
<td>NRS PSFS DPA KOOS</td>
</tr>
<tr>
<td>Brody (2015)26</td>
<td>Experimental Case Series</td>
<td>N=2 (1M, 1F)</td>
<td>MC 'squeeze' technique</td>
<td>None</td>
<td>DPA PSFS Knee ROM NRS</td>
</tr>
<tr>
<td>Rhinehart (2015)29</td>
<td>Case Study</td>
<td>N=1F</td>
<td>MC 'squeeze' technique NWB tibial IR WB tibial IR glide WB tibial IR glide combined with a distal anterior tibiofibular glide lateral tibial glide MC tibial IR glide tapping technique</td>
<td>None</td>
<td>DPA NRS LEFS GRoC PSFS CSIM Knee ROM</td>
</tr>
</tbody>
</table>

M = male; F = female; MC-Mulligan Concept; NRS – Numeric Pain Rating Scale; PSFS – Patient-Specific Functional Scale; DPA – Disability in the Physically Active Scale; KOOS – Knee injury and Osteoarthritis Outcomes Score; ROM – Range of Motion; LEFS – Lower Extremity Functionality Scale; GRoC – Global Rating of Change; CSIM – Client Specific Impairment Measure; NWB – Non-weight bearing; WB – Weight-Bearing; IR – Internal Rotation

Table 3. Assessment of Included Studies

<table>
<thead>
<tr>
<th>Study Author (Date)</th>
<th>Study Design</th>
<th>Scale Used</th>
<th>Scale Score</th>
<th>Level of Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasturi (2020)28</td>
<td>RCT</td>
<td>PEDro Scale / D&amp;B</td>
<td>4/10 / 22/32</td>
<td>Level 2</td>
</tr>
<tr>
<td>Hudson (2018)21</td>
<td>RCT</td>
<td>PEDro Scale / D&amp;B</td>
<td>6/10 / 26/32</td>
<td>Level 2</td>
</tr>
<tr>
<td>Hudson (2016)27</td>
<td>Case Series</td>
<td>JBI Checklist</td>
<td>8/10</td>
<td>Level 4</td>
</tr>
<tr>
<td>Brody (2015)26</td>
<td>Case Series</td>
<td>JBI Checklist</td>
<td>9/10</td>
<td>Level 4</td>
</tr>
<tr>
<td>Sanchez (2017)21</td>
<td>Case Study</td>
<td>CARES Checklist</td>
<td>10/12</td>
<td>Level 4</td>
</tr>
<tr>
<td>Rhinehart (2015)29</td>
<td>Case Study</td>
<td>CARES Checklist</td>
<td>9/12</td>
<td>Level 4</td>
</tr>
</tbody>
</table>

RCT – Randomized Control Trial; CARE - Case Report guidelines; JBI – Joanna Briggs Institute; PEDro Physiotherapy Evidence Database; D&B – Downs and Black Checklist

24 hours.38,39 The minimal clinically important difference (MCID) on the NRS is 2 points or a 53% reduction indicating a “much better” improvement in symptoms.40

FUNCTION

The PSFS was used to assess function. All six studies utilized the PSFS, where patients choose and rate functional or personally important tasks from 0 (unable to perform activity) to 10 (able to perform activity at pre-injury level).34,35,41 The MCID for the PSFS is 3 points in orthopedic knee conditions.41

MULTI-DIMENSIONAL HEALTH STATUS

Five studies used the DPA scale to assess the patient’s perception of disability as a result of their injury.42 The DPA scale consists of 16 items scored from 1 (no problem) to 5 (the problem(s) severely affect me).42,43 The scores for each item are totaled and then 16 is subtracted from the total score to provide the DPA score; scores range from 0–64, with high scores indicating more severe disability.42 The MCID value for the DPA scale is a change of 9 points in acute injuries and a change of 6 points in chronic injuries.42

Two studies used the KOOS, which is a self-administered outcome measure used to assess a patient’s perception of
their knee injury and ability to complete usual activities.\textsuperscript{44} The KOOS assesses five different subscales specific to knee injury: pain, symptoms, activities of daily living, sport and recreational function, and knee-related quality of life over the past week.\textsuperscript{44} The KOOS includes 42 items across the five subscales with each item scored on a Likert scale from 0 (no problem or never) to 4 (extreme problem or always); the score is then converted to a 0-100 scale with a lower score representing more severe problems.\textsuperscript{44}

SECONDARY OUTCOMES

One study used the LEFS to assess a patient’s perceived disability with a 20-item questionnaire designed to assess a patient’s perceived level of difficulty completing different activities due to lower extremity injury.\textsuperscript{45} The LEFS items are scored on a Likert scale from 0 (extreme difficulty or unable to perform) to 4 (no difficulty) and the score for each is summed together for a total score; the maximum score on the LEFS is 80 points and indicates no functional limitations.\textsuperscript{45}

One study used the GRoC which is a single-item measure to assess the patient’s perceptions of their overall improvement since the initial treatment.\textsuperscript{46} The GRoC is scored on a 15-point Likert Scale ranging from -7 (a very great deal worse) to +7 (a very great deal better).\textsuperscript{47} A change in score of 5 points or greater on the 15-point GRoC scale represents a clinically meaningful change.\textsuperscript{48}

Three studies used range of motion (ROM) as a clinician-reported outcome measure used to assess joint motion. The normative ROM for knee flexion and extension ranges from 132.9° to 142.3° and 0.5° to 2.4° respectively.\textsuperscript{49}

One study used the CSIM, which is a specific movement or muscle contraction that causes pain or is difficult for a patient to perform; the CSIM is rated on a scale from 0 (no difficulty or pain) to 10 (maximum difficulty or pain).\textsuperscript{50} The CSIM is used in the Mulligan Concept to identify what is painful for the patient and help the clinician use the appropriate directional force or glide to relieve pain throughout the previously painful movement. No validation of the CSIM has been done to date.

RESULTS

A total of 139 articles were initially identified from the search and 133 articles were excluded due to either being duplicates or not meeting the inclusion and exclusion criteria (Figure 1). A total of six articles met the inclusion and exclusion criteria for full-text review and were included in the analysis (Table 2). All eligible articles yielded a total of 72 subjects (Male=48, Female=24) ranging in age from 14-62 years. All patients were clinically diagnosed with a meniscal pathology through a physical exam; participant demographics and physical exam diagnostic criteria are presented in Table 1.

QUALITY ASSESSMENT

Six studies were included in the final analysis covering multiple designs and levels of evidence.\textsuperscript{21,24,26–29} Two RCTs, two case series, and two case studies were evaluated for quality using the appropriate measures (Table 3). The two RCTs were graded down to Level 2 because of quality: both were scored as six or less on the PEDro scale indicating concerns with methodological quality. However, in the D&B checklist the Hudson RCT\textsuperscript{21} fell in the "excellent" range (26/32) while Kasturi\textsuperscript{28} fell in the "good" range (22/32). The case series were graded above a 6/10 demonstrating low risk of bias. Both case studies were assessed with the CARES checklist used for the reporting of a case study; both were able to answer "yes" to 75% or higher of the questions in the checklist. Table 1 details the assessment of each article included.

INTERVENTION PROTOCOL AND GENERAL FINDINGS ASSESSMENT

The total number of treatments used varied between studies. Kasturi\textsuperscript{28} was the only study without the total number of treatments reported; however, data was reported at three time points during the study. The number of treatments reported in the other studies varied between two and six.\textsuperscript{21,24,26,27,29} The time between treatments varied across all six studies ranging from 24 hours to 14 days.\textsuperscript{21,26} The specific intervention protocols and study timelines are described in Table 4.

Some of the patients were allowed to continue participation during treatment while other authors did not specify the amount of participation or restriction during treatment. Kasturi\textsuperscript{28} did not report on the level of activity before, during, or after treatment. Hudson et al\textsuperscript{21} only reported on discharge criteria and did not specify participation parameters. Sanchez\textsuperscript{24} reported that all the patients returned to participation but did not describe participation during the intervention. In the case series, Hudson et al\textsuperscript{27} reported that the patients were able to continue participation throughout treatment and returned to previous levels of activity. Brody et al\textsuperscript{26} and Rhinehart\textsuperscript{29} only reported that patients were able to return to previous levels of participation following the MC MWM treatment. No researcher reported any adverse reaction to the treatment or worsening of the symptoms following treatment.

Similar results were reported across the two RCTs.\textsuperscript{21,28} Kasturi\textsuperscript{28} reported both groups improved with rehabilitation; however, the treatment group with MC MWM had a statistically significant improvement in comparison to the control group consisting of conventional rehabilitation. Hudson et al\textsuperscript{21} also demonstrated statistically significant results for those in the treatment group and crossover group compared to the sham treatment.
Table 4. Intervention Protocol

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Intervention Protocol</th>
<th>Timeline</th>
<th>Number of Treatments</th>
</tr>
</thead>
</table>
| Kasturi (2020) | IG: MC 'Squeeze' technique with conventional therapy  
- 3x10 in one session  
Conventional therapy:  
- Static quadriceps, vastus medialis obliques, and hamstring strengthening  
- Active hip, knee, ankle ROM exercises  
- Seated multiple angle isometric exercises  
- AROM and strengthening for the unaffected lower limb  
- Gait training given on parallel bar in front of the mirror  
- All exercises were repeated ten times with 10 sec hold and relaxed each time.  
Control Group: conventional therapy only | Treatment was conducted for 6 weeks; frequency of treatment sessions (e.g., 1/week, 2/week) was not reported. | Not provided |
| Hudson (2018) | Intervention Group:  
- MWM: MC 'Squeeze' technique  
- 3 x 10 with a minimum of 30 seconds of rest in between each set  
Control Group:  
- Used same protocol as IG, but with a sham Mulligan using a different hand placement and amount of force  
- No activity restriction  
Crossover Group:  
- Received MC 'Squeeze' treatment after not reaching discharge criteria in the sham group | 14-days  
24-72 hours in between each Tx  
Crossover group had an additional 14-day treatment period with the 'Squeeze' technique after the sham treatment if they had not recovered | ≤ 6  
Crossover group had an additional 1-6 treatments with the 'Squeeze' technique after the sham treatment |
| Sanchez (2017) | MWM - MC 'Squeeze' technique  
Visit 1:  
- Tibial IR MWM with squat 3 x 10  
Visit 2:  
- MC 'Squeeze' 3 x 10  
Visit 3:  
- MC 'Squeeze' 2 x 10  
- Tibial IR MWM with terminal knee extension 3 x 10 | 11-days | 3 |
<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Intervention Protocol</th>
<th>Timeline</th>
<th>Number of Treatments</th>
</tr>
</thead>
</table>
| Hudson (2016)27 | - MC 'squeeze' technique was administered according to Mulligan Concept principles.  
- All participants were treated until discharged | Average 14.2 days (SD = 5.68 days)  
Ranged from 2 to 21 days | Ranged from 2 to 6 treatment sessions |
| Brody (2015)26 | - MC 'squeeze' Tx given by same Mulligan trained clinician  
- 3 sets of 10 reps in PWB during 1st Tx.  
- 3 sets of 10 in squat during 2nd Tx. | Patient 1: 21 days  
Patient 2: 15 days | Both patients: 2 |
| Rhinehart (2015)29 | Visit 1:  
- 3x10 NWB tibial IR MWM flexion/extension  
- 3x10 WB tibial IR MWM knee flexion  
- 3x10 WB tibial IR MWM with anterior tib/fib glide for dorsiflexion  
- Taped the tibial IR glide using Coverall and Leukotape  
Visit 2:  
- 1x10 NWB tibial IR MWM flexion/extension  
- 2x10 WB tibial IR MWM knee flexion  
Visit 3:  
- 2x10 lateral tibial glide while walking up steps  
- 2x10 tibial IR with lateral tibial glide while walking up steps  
- 2x10 MC 'squeeze' technique while walking up steps  
- Taped the tibial IR glide using Coverall and Leukotape  
Visit 4:  
- 2x10 MC 'squeeze' technique while lunging 3x10 standing forward lunge with medial tibial glide | 9-days | 4 |

MWM = Mobilization with Movement; MC = Mulligan Concept; ROM = Range of Motion; AROM = Active Range of Motion; IG = Intervention Group; Tx = Treatment; CG = Control Group; SD = Standard Deviation; IR = Internal Rotation; PWB = Partial weight bearing; NWB = Non-weight bearing; WB = Weight bearing
Table 5. Numeric Pain Rating Scale Results

<table>
<thead>
<tr>
<th>Study</th>
<th>Intake</th>
<th>Discharge</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasturi (2020)28</td>
<td>IG: 7.35 ± 1.18</td>
<td>IG: 1.1 ± 0.79</td>
<td>IG: 6.25 pt ↓*</td>
</tr>
<tr>
<td></td>
<td>CG: 7.2 ± 0.15</td>
<td>CG: 3.05 ± 1.23</td>
<td>CG: 4.15 pt ↓*</td>
</tr>
<tr>
<td>Hudson (2018)21</td>
<td>IG: 2.64 ± 0.89</td>
<td>IG: 0.44 ± 0.44</td>
<td>IG: 2.2 pt ↓*</td>
</tr>
<tr>
<td></td>
<td>CG: 3.67 ± 2.50</td>
<td>CG: 2.42 ± 1.96</td>
<td>CG: 0.66</td>
</tr>
<tr>
<td></td>
<td>COG: 3.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sanchez (2017)24</td>
<td>3 (Worst score)</td>
<td>0 (worst)</td>
<td>3 pt ↓*</td>
</tr>
<tr>
<td>Hudson (2016)27</td>
<td>4.32 (Average)</td>
<td>0.07 (average)</td>
<td>4.25 pt ↓*</td>
</tr>
<tr>
<td>Brody (2015)26</td>
<td>Patient 1: 4 (average)</td>
<td>Both patients: 0 (average)</td>
<td>Patient 1: 4 pt ↓*</td>
</tr>
<tr>
<td></td>
<td>Patient 2: 8 (average)</td>
<td></td>
<td>Patient 2: 8 pt ↓*</td>
</tr>
<tr>
<td>Rhinehart (2015)29</td>
<td>4.7</td>
<td>0.833</td>
<td>3.87 pt ↓*</td>
</tr>
</tbody>
</table>

* Denotes minimal clinically important difference; IG – Intervention Group; CG – Control Group; COG – Crossover Group; pt – point

** PRIMARY OUTCOMES **

** PAIN **

In the six included papers, the researchers reported decreases in pain that were either statistically significant or met the MCID of a two-point change on the NRS.21,24,26–29,40 All of the participants who received MC MWMs had a complete or near-complete resolution of pain (Table 5). Kasturi28 reported no significant difference after day one of treatment (\( p = 0.698 \)) but a significant difference in NRS scores between the control group and the intervention group at four weeks with a mean difference of 1.65 (\( p = 0.001 \)), six weeks post intervention with a mean difference of 1.95 (\( p = 0.001 \)). Both groups had a reduction in pain on the NRS that exceeded the MCID. In their RCT, Hudson et al.21 did not report a statistically significant difference between the sham-control group and the intervention group after the final treatment for pain; however, the intervention group had over a two-point average reduction on the NRS and met the MCID, while the sham-control group did not meet the MCID for the NRS after the final treatment. Additionally, all the participants in the intervention group scored a two or less on the NRS scale following the final treatment.21

In the two included case series26,27 the researchers reported decreases in pain in as little as two treatments26 to an average of five treatments.27 In both cases, pain was reduced to near zero at discharge on the NRS.26,27 The total number of patients treated between the two-case series was seven with five of them from the Hudson et al.27 study. Two additional patients have been reported in the literature through two case studies.27,29 Both patients reported decreased pain in as few as three treatments.27,29 Both studies met the MCID with a greater than two-point change at discharge.27,29 In addition, both authors reported that the patients had less than 1/10 on the NRS at discharge.27,29

** FUNCTION **

Patient reported improvement in function was found on the PSFS (Table 6) in all six studies and the results were either statistically significant or met the MCID.21,24,26–29 In both RCTs,21,28 a statistically significant difference in the PSFS scores of the participants in the intervention group compared to the control group were found across each of the measured time points.21,28

Additionally, in a case series by Hudson et al.,27 each of the participants had an increase of at least 3 points on their PSFS by the time of discharge, meeting the MCID of 3.27,51 Furthermore, changes in patient reported function were reported to be statistically significant (\( p = 0.003 \)) and a large effect size (\( d = 5.01 \)) was reported.27,52 The other case series by Brody et al26 did not include inferential statistical analysis; however, both patients reported PSFS improvements which met the MCID value for the PSFS.

In a case study by Rhinehart,29 the participant had an increase in their average PSFS score by 4.75 points from initial visit to discharge (nine days), which also met the MCID for the PSFS. In another case study,24 the participant improved 2 points on their PSFS to reach the maximum 10 points from initial visit to discharge.

** MULTIDIMENSIONAL HEALTH STATUS **

** DISABLEMENT IN THE PHYSICALLY ACTIVE SCALE (DPA) **

In each of the five studies that reported on the DPA scale, either the MCID was met or a statistically significant change in DPA scores was reported (Table 7) indicating the patient’s perceived disability improved with treatment.21,24,26,27,29 The DPA scale was utilized in one RCT and a statistically significant difference (mean difference of 8.78 points; \( p = 0.013 \)) was found between the MC MWM treatment group and the sham group.21 In the case series by Hudson et al.,27 each of the five participants had an improvement in their DPA scale at discharge: three of the five participants reported changes exceeding the MCID criterion, while the other two participants reported DPA scale scores within the reported ranges of healthy people prior to starting treatment.27,42 Brody et al.26 reported that the DPA score increased from intake to discharge for one participant and noted that the increase was due to increased life stress. In the two case studies, both patients reported a decrease in their DPA score with each visit.24,29

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* Denotes minimal clinically important difference; IG – Intervention Group; CG – Control Group; COG – Crossover Group; pt – point

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Table 6. Patient-Specific Functional Scale Results

<table>
<thead>
<tr>
<th></th>
<th>Intake</th>
<th>Discharge</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasturi (2020)</td>
<td>IG: 3.39 ± 1.18</td>
<td>IG: 8.49 ± 0.61</td>
<td>IG: 5.1 pt ↑*</td>
</tr>
<tr>
<td></td>
<td>CG: 3.89 ±0.81</td>
<td>CG: 7.11 ±0.84</td>
<td>CG: 3.22 pt ↑*</td>
</tr>
<tr>
<td>Hudson (2018)</td>
<td>IG: 3.67 ±1.72</td>
<td>IG: 9.50 ±1.85</td>
<td>IG: 5.83 pt ↑*</td>
</tr>
<tr>
<td></td>
<td>CG: 6.45 ±1.57</td>
<td>CG: 7.00 ±2.07</td>
<td>CG: 0.55 pt ↑</td>
</tr>
<tr>
<td></td>
<td>COG: 5.80</td>
<td>COG: 9.00</td>
<td>COG: 3.20 pt ↑*</td>
</tr>
<tr>
<td>Sanchez (2017)</td>
<td>8 (average)</td>
<td>10.0 (average)</td>
<td>2 pt ↑</td>
</tr>
<tr>
<td>Hudson (2016)</td>
<td>3.4 (average)</td>
<td>10.0 (average)</td>
<td>6.6 pt ↑*</td>
</tr>
<tr>
<td>Brody (2015)</td>
<td>Patient 1: 5.33 (average)</td>
<td>Patient 1: 8.67 (average)</td>
<td>Patient 1: 3.34 pt ↑*</td>
</tr>
<tr>
<td></td>
<td>Patient 2: 2.0 (average)</td>
<td>Patient 2: NT</td>
<td>Patient 2: N/A</td>
</tr>
<tr>
<td>Rhinehart (2015)</td>
<td>4.0</td>
<td>8.75</td>
<td>4.75 pt ↑*</td>
</tr>
</tbody>
</table>

* Denotes minimal clinically important difference; IG = Intervention Group; CG = Control Group; COG = Crossover Group; Tx = treatment; pt = point; NT = not tested; N/A = Not applicable

Table 7. Disablement in the Physically Active Scale Results

<table>
<thead>
<tr>
<th></th>
<th>Intake</th>
<th>Discharge</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasturi (2020)</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hudson (2018)</td>
<td>IG: 23.92 ±10.05</td>
<td>IG: 9.00 ±8.12</td>
<td>IG: 14.92 pt ↑*</td>
</tr>
<tr>
<td></td>
<td>CG: 24.91 ±11.96</td>
<td>CG: 18.55 ±14.05</td>
<td>CG: 6.36 pt ↓*</td>
</tr>
<tr>
<td></td>
<td>COG: 26.6</td>
<td>COG: 10.4</td>
<td>COG: 16.2 pt ↓*</td>
</tr>
<tr>
<td>Sanchez (2017)</td>
<td>16</td>
<td>6</td>
<td>10 pt ↓*</td>
</tr>
<tr>
<td>Hudson (2016)</td>
<td>25.6 (Average)</td>
<td>7.4 (average)</td>
<td>18.2 pt ↓*</td>
</tr>
<tr>
<td></td>
<td>Patient 2: 40</td>
<td>Patient 2: NT</td>
<td>Patient 2: N/A</td>
</tr>
<tr>
<td>Rhinehart (2015)</td>
<td>46</td>
<td>46 pt ↓*</td>
<td></td>
</tr>
</tbody>
</table>

* Denotes minimal clinically important difference; IG = Intervention Group; CG = Control Group; COG = Crossover Group; Tx = treatment; pt = point; NT = not tested; N/A = Not applicable; ↑ Increase in DPA score was attributed to other aspects of the patient’s life causing them stress

KNEE INJURY AND OSTEOARTHRITIS OUTCOME SCORE

Two of the studies included the KOOS outcome measure to assess the patient’s perception of their knee injury and dysfunction. In a case series, Hudson et al. found the average change on the KOOS across participants was 28.56 ± 5.68 point increase (i.e., improvement) from the initial exam to discharge, which was an average of 14.2 days across the five participants. In a randomized controlled trial, Hudson et al. observed an average increase (i.e., improvement) of 13.82 ± 10.94 points on the KOOS in participants in the MC ‘Squeeze’ treatment group, while there was only a 9.07 ± 11.15 average increase in the sham group. Five participants crossed over and completed the MC ‘Squeeze’ treatment and reported a mean increase of 21.28 ± 11.38 from completion of sham trial to completion of MC ‘Squeeze’ trial.

SECONDARY OUTCOMES

LOWER EXTREMITY FUNCTIONAL SCALE

The LEFS was included as an outcome measure in a single case report. Researchers reported the patient had an initial score of 55. After four treatment sessions over the course of 9 days, the patient had attained a score of 80 points, which is the highest score possible indicating no perceived functional limitations were identified by the patient on the LEFS. Additionally, this patient maintained this score at both the one-week and one-month follow up after discharge.

GLOBAL RATING OF CHANGE

The GrOC was used as an outcome measure in the case report by Rhinehart. The patient reported a score of +6 (A great deal better) following the first treatment session. The discharge exam for this patient occurred nine days after initial treatment, and a GrOC score of +7 (A very great deal better) was reported. The GrOC score was maintained at both the one-week and one-month follow-up appointments.

RANGE OF MOTION

Three of the studies included knee ROM as an outcome measure (Table 8). In two of the studies, the patients had full knee range of motion by discharge. Additionally, in their case report, Rhinehart found improvements in ROM were maintained through the one-month follow-up. In an RCT, the researchers found a statistically signifi-
Table 8. Knee Active Range of Motion (AROM) Results

<table>
<thead>
<tr>
<th></th>
<th>Intake</th>
<th>Discharge</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CG: Flexion: 102.75°</td>
<td>CG: Flexion: 121°</td>
<td>CG: 18.25°↑</td>
</tr>
<tr>
<td>Hudson (2018)²¹</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sanchez (2017)²⁴</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hudson (2016)²⁷</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IG = Intervention Group; CG = Control Group; N/A = Not applicable; * = Type of ROM measured was not specified

significant mean difference of 7.5 (p < 0.001) in ROM in the intervention group compared to the control group.²⁸

CLIENT SPECIFIC IMPAIRMENT MEASURE

The Client Specific Impairment Measure (CSIM) outcome was included in a case report²⁹ where the patient identified a body-weight squat and forward lunge as the motions causing pain and reported a 4 out of 10 for the squat and a 6 out of 10 for the lunge before treatment for pain/difficulty.²⁹ Following the first treatment session, the CSIM scores improved to a 2; after the second treatment session, the reported CSIM scores were a 0 indicating no pain or difficulty with a body-weight squat or forward lunge. Scores of 0 on the CSIM were maintained through discharge, one-week, and one-month follow up.²⁹

FOLLOW-UP RESULTS

Follow-up data collection post-discharge (Table 9) was only conducted in two²⁶,²⁹ of the included studies. In the case report by Rhinehart,²⁹ the patient completed four treatment sessions over the course of nine days and results were maintained or improved at follow-up. Brody et al²⁶ obtained follow-up results from one participant, 21 weeks (~5 months) post discharge. The participant received two treatment sessions and was discharged three weeks after their initial evaluation, also reporting maintained or improved scores at follow-up.²⁶

DISCUSSION

Researchers have reported that appropriate physical examination procedures can result in accurate diagnosis of meniscal pathology.⁶,⁷ Accurate identification of the condition, as well as determining if the patient will respond to conservative therapy, is important for healthcare professionals and researchers. The MC includes MWMs such as the ‘Squeeze’ technique, tibial IR, and tibial ER proposed to rapidly restore pain-free, functional ROM for patients with suspected meniscal injury which could enhance conservative care protocols and outcomes. The MWM techniques, however, have not been critically appraised via a systematic review. The purpose of this study was to evaluate the effectiveness of MC MWMs on patient-reported pain, function, and multi-dimensional health status in patients with clinically diagnosed meniscus pathologies.

PAIN

Pain severity was assessed using the NRS in each of the included studies²¹,²⁴,²⁶–²⁹ The application of MWMs in cases of clinically diagnosed meniscal pathology produced substantial improvements in pain severity. Improvements included complete or near-complete resolution of pain in as little as one week of treatment²⁶ or in as few as one or two treatment sessions.²⁴,²⁶ Asymptomatic meniscal tears are common among healthy people indicating that the damaged meniscus may not need to be removed; thus, when pain is a primary complaint, conservative pain reduction therapies that successfully resolve this complaint may be sufficient.⁵ The use of MC MWMs, and specifically the MC ‘Squeeze’ technique, were found to be effective interventions for pain reduction in clinically diagnosed meniscal pathology over shorter durations (e.g., one month-follow-up) in the included literature. The included studies did not identify evidence to support the long-term effects of these interventions (e.g., length of pain resolution, relationship to OA development, etc.), patient-applied application of the techniques for symptom management, or outcomes of the techniques being applied as multimodal rehabilitation protocols. Thus, clinicians and researchers should consider measuring and assessing longer-term outcomes of these techniques, outcomes from patient-application of the techniques, and how the incorporation of other intervention or exercise protocols may influence patient outcomes.

FUNCTION

The PSFS was used in all studies to assess patient-perceived functional improvements. The reported PSFS changes met the MCID and were statistically significant indicating the
technique not only provided a reduction in pain but also restored function, as defined by the patient. The findings are valuable because pain and function are the primary symptoms for which patients seek treatment.\textsuperscript{11} In Kise et al,\textsuperscript{11} patients were divided into two groups following diagnosis of meniscal injury where one group was given exercise therapy alone while the other group received surgery alone. The exercise therapy group and those who underwent meniscal repair showed no significant difference after two years indicating a need for a treatment that will restore function and allow continued activity for otherwise healthy patients. While the MC ’squeeze’ technique seems promising to restore function in the short term, only two of the studies included any long-term follow-up\textsuperscript{26,29} with the longest follow-up point being 21 weeks post-discharge.\textsuperscript{26} Neither of the RCT’s\textsuperscript{21,28} found any long-term follow-up with the patients to see how long the treatment result lasted. The gold standard of surgical repair is not necessarily a long-term solution for the treatment of meniscal pathologies as some patients who have had surgery have needed additional surgery in as few as two years, and in the event of a failed repair that is asymptomatic, it is advisable to leave the meniscus alone instead of performing resection or another repair.\textsuperscript{16} Therefore, alternative treatment approaches are needed, and the MC ’squeeze’ technique could be a valuable tool for the mitigation of symptoms to restore function when a meniscal pathology is suspected.

**MULTIDIMENSIONAL HEALTH STATUS**

The DPA scale assesses physical impairment (e.g., pain, function) and quality of life in unique constructs. The included studies provide evidence that the MC ’squeeze’ technique improved multidimensional health status as measured by the DPA scale. Four of the studies\textsuperscript{21,24,27,29} found a statistically significant change (i.e., improvement) in DPA scores following treatment. Brody,\textsuperscript{26} however, identified impaired quality of life (QOL) score on this outcome measure in her case study through the course of treatment. The case report design allowed patient questioning that revealed the QOL impairment was perceived to be due to other life-related stress independent of knee pain. The implications of catching a change in life stress related to or independent of presenting pathologies could have long-term treatment implications by informing future care decisions.\textsuperscript{54} Overall, the MC ’squeeze’ technique restored physical and QOL impairments as measured by the DPA scale, which is expected because physical improvements (e.g., pain reduction, increased function) are likely to correlate with improved QOL.\textsuperscript{55}

The use of the KOOS could have addressed the lack of long-term follow-up data as it has been recommended as a long-term outcome measure for three months, six months, and a year.\textsuperscript{44} However, the researchers who included the KOOS did not collect discharge data further than 14 days after intake. The studies\textsuperscript{21,27} that used the KOOS revealed meaningful improvement in KOOS scores; however, KOOS data collected at wider intervals over a longer duration would have provided greater insight into long-term intervention effectiveness.

**SECONDARY OUTCOMES**

The secondary outcome measures included in the different studies were the LEFS, GRoC, ROM, CSIM, and follow-up treatment. Only Rhinehart\textsuperscript{29} reported on the LEFS and GRoC, and both measurements revealed patient improvement during the study. These results were corroborated with other scales (e.g., DPA KOOS) also used in the study and revealed improvement in pain, function, and QOL.

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**Table 9. Follow-up Results**

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>Initial Evaluation</th>
<th>Discharge</th>
<th>Follow-up</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRS (0-10)</td>
<td>4.7 (Average)</td>
<td>0.83</td>
<td>0</td>
<td>Follow-up was conducted at both 1-week and 1-month after discharge and the patient had the same scores at both time points</td>
</tr>
<tr>
<td>PSFS (0-10)</td>
<td>4 (average)</td>
<td>8.75</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>DPA</td>
<td>46</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>LEFS (0-80)</td>
<td>55</td>
<td>64</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>GRoC</td>
<td>N/A</td>
<td>+7</td>
<td>+7</td>
<td></td>
</tr>
<tr>
<td>CSIM (0-10) Squat; Lunge</td>
<td>4/10; 6/10</td>
<td>0/10; 0/10</td>
<td>0/10; 0/10</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Brody (2015)\textsuperscript{26}</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRS (0-10)</td>
</tr>
<tr>
<td>PSFS (0-10)</td>
</tr>
<tr>
<td>• Squatting</td>
</tr>
<tr>
<td>• Knee extension</td>
</tr>
<tr>
<td>• Post-activity</td>
</tr>
</tbody>
</table>

NRS – Numeric Pain Rating Scale; PSFS – Patient-Specific Functional Scale; DPA – Disability in the Physically Active Scale; LEFS – Lower Extremity Functional Scale; GRoC – Global Rating of Change; CSIM – Client-Specific Impairment Measure.

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International Journal of Sports Physical Therapy
Rhinehart29 study was the only study to include the CSIM; the CSIM data collected supported the PSFS and NRS data corroborating increased function and decreased pain following treatment. It is not known, however, if CSIM data provides unique or redundant information compared to other measures (e.g., NRS, PSFS).

Joint ROM was assessed in three of the articles26,28,29 included in this review and was found to have increased following treatment. The increase in ROM was supported by patient-reported information found in other measures (e.g., NRS, PSFS, DPA scale) providing disease-oriented evidence supporting the patient-reported evidence. An advantage of assessing ROM in addition to patient reported outcomes is ROM provides quantifiable disease-oriented evidence supporting improvement. The collection of disease-oriented outcomes, in addition to patient-oriented outcomes, should be considered for future studies to further understand the effects of the MC ‘Squeeze’ technique along with tibial IR and ER MWM’s.

LIMITATIONS

Limitations are present in this review. While all studies found positive findings for patients treated using the MC techniques, the quality of evidence should be considered. Only two RCTs were identified,21,28 and case reports and case series made up two-thirds of the studies included in this review. A meta-analysis was unable to be conducted due to the limited number of published studies and the heterogeneity of the included studies. The lack of long-term follow-up in the included studies is also a limitation, as only two studies26,29 included follow up visits with participants’ post-discharge. The collection of longer-term outcomes, including patient-oriented and disease-oriented, would be valuable in re-determining the effectiveness of MC MWM for the treatment of meniscal pathologies. Thus, further high-quality RCTs are needed. The included studies generally lacked comparison to sham treatments, multi-modal conservative treatment, diagnostic imaging, or surgical intervention. Finally, the included studies generally included adolescent through middle aged adults of a physically active population. While other studies have successfully used the MC for other knee pathologies (e.g., osteoarthritis) in older populations,56 the findings of the systematic review should be applied with caution across all populations.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future research is needed on the MC ‘Squeeze’ technique along with other MC techniques as indicated by the patient case and their effectiveness in the treatment of clinically diagnosed meniscal pathologies. Long-term follow-up with patients from six months to three years would be helpful in better understanding how effective the treatment is at reducing the need for surgery. Higher level RCTs with a control or sham treatment group assessing a wider age range would also be beneficial. Lastly, studies using diagnostic imaging (e.g., MRI) or surgery to confirm the presence, type, and location of a meniscal pathology would help to further assess the effectiveness of the MC treatment for meniscal lesions and provide insight on types of meniscal pathology that may not respond to MC intervention.26,29

CONCLUSION

The results of this systematic review provide initial support for the use of MC MWM techniques for conservative treatment of patients with a clinically diagnosed meniscal pathology. The MC MWMs reduced pain, increased function, increased knee range of motion, while decreasing patient reported symptoms of multidimensional health status impairment related to meniscus pathology. Future research should focus on using the MC MWM techniques as adjunct or stand-alone interventions, in more diverse patient populations, in imaging confirmed meniscal pathology, and with longer-term follow-up to better understand the effectiveness of the intervention.

CONFLICTS OF INTEREST

All authors declare that they do not have any conflict of interests with any of the topics discussed in this manuscript.

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REFERENCES


Application of Shear-Wave Elastography in the Evaluation of Hamstring Stiffness in Young Basketball Athletes

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Keywords: hamstring stiffness, shear wave elastography, targeted neuromuscular training, hamstring quadriceps ratio, ultrasonography

https://doi.org/10.26603/001c.55757

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Background

Previous literature has postulated a relationship between greater hamstring stiffness and a higher risk of sustaining injury. Shear wave elastography (SWE) presents a relatively new means for non-invasive evaluation of soft tissue elasticity pre- and post- injury or intervention.

Purpose

(1) To establish baseline hamstring stiffness measures for young competitive athletes and (2) determine effect of targeted neuromuscular training (TNMT) on shear wave stiffness of the hamstring.

Study Design

Un-blinded, prospective, non-randomized, cohort study.

Methods

Six-hundred forty-two lower extremities from 321 high school and collegiate basketball athletes (177 F: 139 M) were examined for hamstring stiffness prior to the start of their competitive basketball season. Teams were cluster assigned to either the control or intervention (TNMT) group. Subjects in the control group underwent regular season activities as directed, with no influence from the research team. For the TNMT group, the research team introduced a hamstring targeted dynamic warm-up program as an intervention focused on activating the hamstring musculature.

Results

Collegiate status was significant to hamstring stiffness for both sexes (p ≤ 0.02), but hamstring stiffness did not correlate to age or sex (r2 ≤ 0.08). Intervention was a significant factor to hamstring stiffness when the hip was positioned in extension (p ≤ 0.01), but not in deeper flexion (p = 0.12). This effect was sex-specific as TNMT influenced hamstring stiffness in females (p = 0.03), but not in males (p > 0.13). Control athletes suffered three HAM injuries; TNMT athletes suffered 0 hamstring injuries.

Conclusion

Higher SWE measurements correlated with increased risk of injury, male sex, and collegiate athletics. TNMT intervention can lessen muscle stiffness which may reduce relate to injury incidence. Intervention effectiveness may be sex specific.
Level of Evidence

INTRODUCTION

Hamstring strain injuries are among the most prevalent injuries sustained by basketball athletes. Previous epidemiological studies show the most common type of injury sustained by professional basketball athletes is a strain, with the hamstring muscle group being the most frequently strained muscle. An evaluation of injuries of the National Basketball Association showed strains comprised up to 57% of reported injuries. Of these strain injuries, 23% related to the hamstring muscle group. Universally, hamstring injuries are one of the most prevalent non-contact injuries in sports with approximately 96% of hamstring injuries occurring in non-contact situations. Although hamstring injuries are common, they can result in a substantial loss of playing time and an increased re-injury rate. The average number of days missed for basketball players who sustained a strain was 7.4 days, with nearly one-third of hamstring strains recurring within the first year of returning to play. High rates of re-injury (12-14% within two years) cause more concern for athletes as re-injuries present with worsening severity and more play time up on re-injury. Previous authors have shown a near doubling of play time lost after hamstring re-injury.

Many variables may play a role in an athlete’s susceptibility to initial hamstring injury and re-injury. Previous literature has postulated a relationship between greater hamstring stiffness and a higher risk of sustaining a hamstring injury. More recent literature has established a connection between increased hamstring stiffness and injury with male sex and past hamstring strain history. Male athletes routinely exhibit greater hamstring stiffness overall when compared to their female counterparts. Hamstring stiffness measurements (kPa) in male athletes are nearly double that of females on both the athlete’s dominant and non-dominant leg. Increased hamstring stiffness is a risk factor in male athletes as it associates with higher hamstring injury rates and a greater proportion of recurrent hamstring injuries. Compared to female athletes, male athletes participating in intercollegiate soccer are 64% more likely to sustain a hamstring injury and are nearly twice as susceptible to hamstring re-injury. In addition, initial hamstring injury can alter the length-tension relationship of the hamstring muscle group, which increases hamstring stiffness. On average, athletes with hamstring injury exhibit 11% higher hamstring stiffness than uninjured counterparts. This mechanical change places greater tension on the hamstring muscle group and may increase the re-injury rate after initial hamstring injury. Additionally, hamstring muscles in a lengthened state exhibit reduced strength and returning to sport without engaging eccentric strengthening in a lengthened muscle state predisposes secondary injury. In correlation with this increased stiffness, athletes with previous hamstring injury are also two to three times more likely to encounter a future hamstring strain than non-injured counterparts. However, increased hamstring stiffness is not universally observed after injury. Apart from associating with injury, muscle stiffness is also modifiable as dynamic stretching, which is known to decrease soft tissue injuries, has also been shown to decrease hamstring stiffness.

Despite this data, findings that correlate injury prevention with hamstring stiffness based on sex are not unilateral. Female college basketball athletes suffer hamstring strains at higher rate than their male counterparts and, as noted, demonstrate decreased hamstring stiffness compared to their male counterparts. Decreases in passive stiffness are unfavorably associated with peak knee flexion torque generation, and knee flexion torque is subsequently associated with injury prevention. Indeed, greater hamstring stiffness has been associated with reduced knee ligament loading and reduced ligament injury risk. Further, patients experiencing back pain exhibit reduced hamstring stiffness compared to matched controls. Accordingly, insufficient muscle stiffness can affect the stability of the surrounding joints. Thus, there is meritorious data to support injury prevention through both increased and decreased hamstring stiffness, but excessive hamstring stiffness is directly related to increased risk of injury to the muscle itself.

In addition to sex differences and hamstring injury history, increasing age and competition level correlate with increased hamstring injury incidence. Previous authors have found that in both football and soccer, surpassing 23 years of age was associated with a higher risk of hamstring injury in athletes compared to their younger counterparts. An estimated 1.78 increase in risk of hamstring injury is associated with every year increase in age after an athlete turns 23. The variation in hamstring injury rate by age is associated with an overall decrease in hamstring strength as individuals age resulting in a muscle imbalance between the quadriceps and hamstring muscle groups, ultimately leading to an increased risk of hamstring injury. Recently Alfuraidi et al. showed decreasing hamstring shear-wave elastography (SWE) stiffness associated with aging in which elderly participants (77-94 years) had on average 16.5% lower hamstring stiffness compared to their young counterparts (20-35 years). Changes in SWE stiffness correlate with muscle weakness associated with aging. The epidemiology of collegiate injuries versus high school injuries shows a more drastic increase in injury rate than those associated with age. The rate of overuse injury in college athletes is 3.28 times higher than in high school athletes. In both high school and college athletes, muscle strain is the most common injury.

The mechanisms of hamstring injury are essential starting points for developing injury prevention programs. Preventive biomechanical techniques are an increasingly popular means of decreasing the risk and incidence of musculoskeletal injuries. Targeted neuromuscular training (TNMT) is a preventative biomechanical technique that consists of exercises designed to activate deficient muscle
groups and encourage muscle co-activation that may be related to injury through movements that mimic those experienced during sport. Additionally, hamstring-based neuromuscular training increases hamstring strength and flexibility over time. As a prevention technique, TNMT addresses muscle stiffness and hamstring to quadriceps strength ratio (H:Q) as plausible risk factors for hamstring injury. This biomechanical technique accomplishes neuromodulation using motor learning principles to focus on optimal control of 3D body positions and movement symmetry. Ultimately, re-establishing connections between nerves and muscles after injury leads to a reduced risk of re-injury. Accordingly, extrapolation of TNMT to non-contact hamstring injuries may prove efficacious in decreasing hamstring strain prevalence and severity by altering baseline biomechanics.

Commonly, hamstring injury is evaluated and diagnosed via dynamic ultrasonography. Classic clinical implementation of ultrasonography, relative to musculoskeletal injury, provides high-resolution imaging of fluid collection around an injured muscle or tendon. These images are highly accurate in the determination of the location and extent of a hamstring injury. Beyond diagnosis and localization, these images have limited use for risk prevention as they fail to provide feedback on mechanical properties or quality of individual muscle. Shear wave elastography (SWE) is a relatively new ultrasound technology that can provide a non-invasive evaluation of soft tissue elasticity. Accordingly, interest in musculoskeletal applications for SWE has grown in the past several years. Ultrasound SWE uses variation in wave propagation to create images that provide an objective measure of tissue elasticity with anatomic specificity. Past researchers have used SWE to evaluate and provide an initial characterization pathologic conditions and injuries of the musculoskeletal system, including, but not limited to, the hamstring muscle group, neck/back muscles, the Achilles’ tendon, and the anterior cruciate ligament. SWE can be used to assess hamstring stiffness at the time of injury, pre, and post-injury providing feedback on injury risk associated with increased stiffness and decreased hamstring stiffness post-injury prevention facilitation. Sex differences in SWE for adolescent basketball athletes have previously been explored, but further study into the relationship between hamstring stiffness and injury rate is necessary to determine whether hamstring stiffness is a primary causal factor for increased injury rate by age and competition level. It is known that increased stiffness at the muscle-tendon unit correlates with greater work absorption, muscle force, and power during countermovement jumps. As muscle stretch is necessary to induce injury and muscle failure occurs at forces greater than maximal isometric contractions, it remains that excessive passive muscle stiffness may predispose muscle tissue to injury. Subsequently, viscoelastic muscle stiffness can be reduced through passive and active stretching which increases both the force and energy absorption until failure. Additional investigation may also elucidate whether alteration of hamstring stiffness is a primary mechanism for injury prevention techniques such as TNMT.

Finally, strong correlation between hamstring stiffness and injury may provide data that suggests that SWE is an optimal tool for determining injury risk and intervention efficacy.

This study’s objectives were to (1) To establish baseline hamstring stiffness measures for young competitive athletes and (2) determine effect of targeted neuromuscular training (TNMT) on shear wave stiffness of the hamstring. Regarding the first objective, it was hypothesized that hamstring stiffness would increase with age in high school basketball and college basketball athletes. Finally, it was hypothesized that TNMT intervention would decrease SWE stiffness in basketball athletes.

METHODS

POPULATION

Six hundred forty-two lower extremities from 321 high school and collegiate basketball athletes (177 F: 139 M; Table 1) were examined for hamstring stiffness across a range of passive hip and knee flexibility prior to the start of their competitive basketball season. Two subjects were excluded from this cohort due to a lack of demographic data. The subject population was a cohort of convenience, recruited from high school and college basketball teams that compete near Rochester, MN, USA. Teams were contacted via a clinical coordinator and offered the opportunity to participate in research with no remuneration. Teams who agreed to participate in the study were cluster assigned to either the Control or intervention (TNMT) group prior to arriving for their first data collection. In this manner, all individuals from the same team were assigned to the same group, intended to reduce potential for data cross-contamination. This design has previously been employed for other training intervention studies. Group assignments occurred in a predetermined order and were assigned to a team based on when they accrued into the investigation. Subject recruitment spanned a three-year period. The current investigation was unblinded to both investigator and participant. Subjects knew they would either receive a targeted training intervention during regular practice warmups or that they would proceed through their season activities unchanged. Pre-season data collection was completed after the start of team activities, but prior to the first competitive game. Post-season testing was completed after the last competitive game. All activities in this study were approved by the institution’s Institutional Review Board (IRB 17-005905). Informed consent was obtained for all subjects over 18 years old. Informed consent and parent/guardian assent were obtained for all subjects under 18 years old.

PROCEDURE

For the control group, no intervention was enacted. These subjects underwent regular season activities as directed by their teams and coaches, with no influence from the research team. For the TNMT group, the research team introduced a hamstring targeted dynamic warm-up program as...
Table 1. Demographics by total number of lower extremities assessed

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Targeted Neuromuscular Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>450</td>
<td>192</td>
</tr>
<tr>
<td>Female</td>
<td>270</td>
<td>92</td>
</tr>
<tr>
<td>Male</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>Average Age</td>
<td>16.18</td>
<td>15.5</td>
</tr>
<tr>
<td>Collegiate Lower Extremities</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>HS Lower Extremities</td>
<td>390</td>
<td>192</td>
</tr>
</tbody>
</table>

*N = total number of lower extremities

an intervention focused on activating the hamstring musculature. This intervention was substituted in place of each team’s regular warm-up activities for 15 minutes twice weekly. Intervention dynamic warm-ups were initiated at the start of the season immediately following the preseason evaluation session and continued until the team was eliminated from playoff contention. As multiple teams were training at the same time, warm-up sessions were overseen either by the lead athletic trainer on the research team (TN) or by additional athletic training staff assigned to the participating schools. These additional staff received instruction from the lead athletic trainer prior to enacting the interventional dynamic warm-up protocol. For the TNMT group, the intervention period lasted approximately 10 weeks in duration for each team. Selection of dynamic warm-up activities were orchestrated by the lead athletic trainer and the program was designed to incorporate elements known to positively affect the hamstring musculature. Specifically, the dynamic warm-up was designed around the incorporation of elements of stretching, skipping/hopping, lunging, jumping/landing, concentric/eccentric hamstring loading, balance, and dynamic range of motion at the core, hip, and knee (APPENDIX 1). Static stretching remains controversial relative to its efficacy for injury prevention; however, multiple studies have indicated that static stretching aids in the reduction of hamstring injuries. Warm-up drills are known to improve neuromuscular control during running. While the value of flexibility and dynamic range of motion remain controversial to hamstring injury prevention, incorporation of eccentric hamstring loading has shown efficacy due to its’ ability to affect hamstring to quadriplex (H:Q) muscle deficits. Lumbopelvic exercises were incorporated as they have demonstrated importance to lower extremity neuromuscular control and injury recovery.

DATA COLLECTION

Ultrasound SWE was used to measure shear wave velocity (kPa) of the biceps femoris muscle at three leg positions (40%, 60%, and 80%) of the maximum passive 90-90 straight-leg raise position for each leg as previously described. Briefly, hamstring flexibility was assessed by a clinician who used a passive knee extension test and a digital inclinometer. Neutral position was considered to be ipsilateral hip and knee flexion both positioned at 90°. The three leg positions (40%, 60%, and 80%) were subject-specific and calculated from the maximum flexibility observed by the clinician. The greater trochanter and femoral condyle were then marked, and the midpoint was identified by the clinician for repeatable placement of the ultrasound transducer both within and between subjects. While lying supine, an assistant moved and held the athlete’s leg at each position for the clinician to measure the biceps femoris stiffness using ultrasound SWE at each position (GE Logiq E9, 9L-D transducer, GE Healthcare, Wauwatosa, WI). Ultrasound SWE captures the Young’s Modulus of soft tissues in kPa based on displacements of the shear wave beam the propagation across the tissue. The Young’s Modulus equation is as follows:

\[ E = 3\rho(\alpha D/t_{\text{max}}) \]

where \( \rho \) is the density of the medium, \( \alpha \) is the Gaussian profile of the beam, \( D \) is a dimensionless diffraction parameter, and \( t_{\text{max}} \) is the rising time. Three SWE images were acquired at each position for average values. Prior to lower limb manipulation, each subject was instructed to fully relax their muscles and allow the assistant to fully support the leg. To ensure that passive muscle stiffness was being obtained, random subjects were selected to be monitored by surface electrodes placed on the medial hamstring muscle. These electrodes would provide real-time audio feedback to ensure the subject did not actively engage the hamstring muscles and that the ultrasound SWE measurements were of passive muscle stiffness. Electrode subject selection was randomized based on the availability of the sensors as several subjects could be undergoing evaluation simultaneously. Throughout pilot testing and the first year of randomly selected subjects, electrodes confirmed that the hamstrings musculature was maintained in a passive state. Beyond this, electrode monitoring was determined to be redundant and ceased. Copious ultrasound gel and minimal pressure was applied to the ultrasound transducer probe to minimize tissue compression and artifact error in tissue stiffness induced from externally applied pressure. Muscle stiffness (kPa) was measured using shear wave velocities from the SWE elastogram calculated via custom designed MATLAB software. Following completion of preseason testing, 105 athletes (206 lower extremities) returned for post-season evaluations that repeated the identical process. Post-season evaluations were conducted within two weeks following each team’s playoff elimination. Whether or not an athlete returned for post-season testing, the Mayo Clinic athletic training staff embedded at each school tracked participants for occurrence of hamstring strain during the basketball season.

STATISTICAL ANALYSIS

For statistical analysis, data were separated by sex and a one-way ANOVA was used to assess hamstring stiffness differences between ages (14-18 years) with a Tukey’s post-hoc test to assess individual differences within each age.
year. A Student’s t-test was used to assess differences in hamstring stiffness relative to competitive level (high school vs. collegiate). Pearson correlations were used to assess association between age and stiffness at each orientation. A 2x2 ANOVA of Intervention (TNMT, Control) vs. Time (Pre-, Post-Season) was used to assess for statistical differences among these groups. Individual differences within groups were assessed via Tukey’s post-hoc test. All statistical analyses were performed in JMP Pro (version 14, SAS Institute, Cary, NC, USA). Significance was set a priori at α < 0.05.

RESULTS

Of the 321 total athletes recruited into this investigation, 103 athletes returned for post-season testing. Of these 103 athletes who completed both pre-season and post-season evaluations, 22 athletes were assigned to the Control group and 81 athletes were assigned to the TNMT group (Table 1).

Age was a significant factor for hamstring stiffness in females at all three orientations (p ≤ 0.05) and in males at the 60% extended orientation (p < 0.01). However, there was no significant linear correlation between age and hamstring stiffness for either sex or any orientation (r² ≤ 0.08). In females, hamstring stiffness peaked at ages 15 and 16 for the 80% orientation and age 15 for the 60% and 40% orientations (Table 2). In males, hamstring stiffness decreased by age 17 relative to age 14 and 15 in the 80% and 60% orientations (Table 2). Collegiate status was significant to hamstring stiffness for females at all orientations and for males at the 80% and 60% orientations. In each of these orientations, the collegiate athletes had significantly greater hamstring stiffness than their high school counterparts (Figure 1).

Table 2. Mean (SD) female hamstring stiffness (kPa) by age and limb orientation

<table>
<thead>
<tr>
<th>Age (Years)</th>
<th>80% Orientation</th>
<th>60% Orientation</th>
<th>40% Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>37.0 (26.3)</td>
<td>43.4 (28.2)</td>
<td>37.0 (20.7)</td>
</tr>
<tr>
<td>15</td>
<td>52.4 (35.7)</td>
<td>58.5 (35.8)</td>
<td>50.0 (28.8)</td>
</tr>
<tr>
<td>16</td>
<td>53.5 (38.8)</td>
<td>52.2 (32.0)</td>
<td>44.2 (26.5)</td>
</tr>
<tr>
<td>17</td>
<td>35.8 (22.9)</td>
<td>44.3 (30.2)</td>
<td>43.2 (26.7)</td>
</tr>
<tr>
<td>18</td>
<td>46.5 (38.3)</td>
<td>45.0 (27.7)</td>
<td>44.3 (28.9)</td>
</tr>
<tr>
<td>Males</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>71.3 (37.3)</td>
<td>73.1 (39.2)</td>
<td>55.3 (33.0)</td>
</tr>
<tr>
<td>15</td>
<td>71.6 (38.4)</td>
<td>80.3 (37.7)</td>
<td>59.5 (32.2)</td>
</tr>
<tr>
<td>16</td>
<td>63.0 (39.5)</td>
<td>60.1 (34.0)</td>
<td>47.1 (27.3)</td>
</tr>
<tr>
<td>17</td>
<td>53.9 (33.1)</td>
<td>52.6 (31.0)</td>
<td>50.8 (29.7)</td>
</tr>
<tr>
<td>18</td>
<td>64.9 (37.6)</td>
<td>69.8 (37.6)</td>
<td>62.4 (31.7)</td>
</tr>
</tbody>
</table>

Figure 1. Hamstring stiffness as recorded by SWE at orientations of 80% (blue), 60% (red), and 40% (green) of peak passive flexion.

At the 80% and 60% position, collegiate basketball players have significantly increased hamstring stiffness relative to their high school counterparts.

Figure 1. Hamstring stiffness as recorded by SWE at orientations of 80% (blue), 60% (red), and 40% (green) of peak passive flexion.

Hamstring stiffness from pre-season to post-season testing (Table 3, Figure 2). Despite being measured with the same SWE machine with the same collection settings, pre-season SWE stiffness was higher in the TNMT group than the control group (p < 0.01).

For female athletes, intervention was a significant factor as hamstring stiffness at the 60% flexibility orientation decreased after TNMT (p = 0.04). TNMT intervention with female athletes approached significance at the 80% flexibility orientation (p = 0.07). TNMT intervention in male athletes did not show a significant change in hamstring stiffness at any orientation (p > 0.13; Table 4).

Across the whole population cohort, the embedded Mayo Clinic athletic training staff were able to track hamstring injury status on 286 athletes (89%). Due to COVID interruption, injury tracking on all collegiate athletes was lost to follow-up. Of the injury-tracked cohort, 193 athletes assigned to the Control group suffered three hamstring injury...
## Table 3. SWE stiffness of hamstring (mean ± SD) by Intervention and Time

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Targeted Neuromuscular Training</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>80%</td>
<td>69.4 ± 35.4†</td>
<td>62.0 ± 33.4†</td>
</tr>
<tr>
<td>60%</td>
<td>67.7 ± 32.4†</td>
<td>60.2 ± 33.4†</td>
</tr>
<tr>
<td>40%</td>
<td>56.1 ± 29.4</td>
<td>50.8 ± 27.3</td>
</tr>
</tbody>
</table>

† = Significant difference (α < 0.05) from 40% flexibility orientation  
* = Significant difference (α < 0.05) from pre-season evaluation

Figure 2. Hamstring stiffness at 80% of peak passive flexion (top) and 40% of peak passive flexion (bottom).  
TNMT reduced hamstring stiffness at the 80% orientation but exhibited no effect at 40%.

## Table 4. SWE stiffness of hamstring (mean ± SD) Pre- and Post-Season for the TNMT Group separated by Sex

<table>
<thead>
<tr>
<th>Position</th>
<th>Males</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>p-value</td>
<td>Pre</td>
</tr>
<tr>
<td>80%</td>
<td>70.8 ± 35.2</td>
<td>66.5 ± 32.5</td>
<td>0.60</td>
<td>57.6 ± 36.0</td>
</tr>
<tr>
<td>60%</td>
<td>66.7 ± 32.3</td>
<td>63.8 ± 34.5</td>
<td>0.55</td>
<td>63.2 ± 32.8</td>
</tr>
<tr>
<td>40%</td>
<td>54.5 ± 30.2</td>
<td>48.2 ± 24.8</td>
<td>0.13</td>
<td>54.6 ± 27.6</td>
</tr>
</tbody>
</table>

* = Significant difference (α < 0.05) from pre-season evaluation

## DISCUSSION

Within the baseline stiffness measures, there were significant sex differences in hamstring stiffness. Males showed significantly greater hamstring stiffness than females for all three flexibility orientations across all ages, 14-18. Neither males nor females showed linear correlation between age and hamstring stiffness. This data rejects the hypothesis that hamstring stiffness would increase with age in high school basketball athletes. Based on this data, hamstring stiffness does not appear to be directly associated with maturational or athletic development.

Researchers have determined that SWE muscle stiffness decreases with ageing from 20 to 94 years along with changes in muscle composition and dysfunction in extracellular fibers; however, hamstring stiffness in adolescent athletes has not previously been disseminated. While neuromuscular efficiency muscle size and contractile force has been shown to increase as adolescents age, data regarding changes in elastic properties remains scarce. Past findings measuring musculotendinous stiffness, joint stiff-
ness, and series elastic component (SEC) stiffness show differences in development and changes to muscle stiffness between the lower and upper extremities in adolescence.\textsuperscript{49,52,53} Previous data showed knee extensor stiffness decreasing as children age and identical measures for elbow flexor stiffness between children and adults.\textsuperscript{49,52,53} Similar studies have yet to be conducted using SWE stiffness as the primary measure of muscle stiffness in adolescence during development. The lack of association between hamstring stiffness and age during adolescence likely indicates a limited influence of pubertal status on muscle stiffness; however, pubertal status was not assessed in the present investigation and further validation is warranted.\textsuperscript{49,54} Likewise, strength was not directly assessed in this study, so it was not possible to determine if SWE stiffness was directly correlated with athlete strength.

Unlike age, level of competition was a significant indicator for increased hamstring stiffness in both sexes. The present data supports the hypothesis that collegiate athletes would have greater hamstring stiffness than high school athletes. In conjunction with increased hamstring stiffness, musculoskeletal injury incidence and sport-specific performance attributes also associate with higher levels of competition.\textsuperscript{25,55} Accordingly, muscle stiffness may be relevant to both injury prevention and sports performance as data from the current study demonstrated that hamstring stiffness is modifiable in female athletes through a minimal regimen of TNMT. Despite these findings, further investigation is warranted to determine whether muscle stiffness has a causal influence on injury prevention within sports as musculoskeletal injuries increase dramatically between high school and collegiate levels.\textsuperscript{27,55}

The present data indicates that a TNMT hamstring warm-up program is likely to decrease hamstring stiffness. The results of the study show lower postseason hamstring stiffness compared to the control group. This supports the hypothesis that TNMT intervention would decrease shear wave stiffness in basketball athletes. Throughout this study three hamstring injuries occurred. Each reported injury occurred in a female high school athlete who was not assigned to the TNMT group. Further investigation is necessary to determine whether dynamic warm-ups targeted to specific muscle groups can offer prevention against soft-tissue injuries in females during athletic participation.

Further, regarding the three injured subjects, the SWE hamstring stiffness in this sub-cohort was different than the whole study cohort, as the three injured athletes individual SWE values were below the cohort mean. This fact remained true regardless of what age bracket the injured subjects were compared against. Relative to the position and limb where SWE was measured, the first injured subject was between 0.12-1.09 standard deviations below the cohort mean, the second injured subject was 0.44-1.02 deviations below the mean, and the third injured subject was 1.12-1.40 deviations below the mean. While this granular data demonstrates that injuries only occurred in athletes with hamstring stiffness deficiencies, the current results are unable to conclusively prove that hamstring stiffness is a primary cause of predisposing athletes to injury during a competitive season.

Optimal hamstring stiffness for basketball athletes is likely to lie along a Bell curve where extremes of extremes of high and low stiffness increase injury risk. It is also interesting to note that overall subject population increased hamstring stiffness with increased extension in the passively manipulated straight leg extension (Table 3), but the injured cohort did not exhibit this trend. Additional investigation is necessary to determine whether these functional mechanics have clinical implications. Further study is also warranted due to preseason differences in the Control and TNMT groups. Measurements were recorded with identical methodology between groups, so it remains unknown as to why the control group was initially less stiff than the TNMT group. It is possible that the TNMT group would have been more susceptible to influence due to their higher initial stiffness.

The current intervention program, TNMT, included eccentric resistance exercise such as Nordic hamstring (NH) eccentric strength training which is associated with reduced injury.\textsuperscript{56–58} However, studies show while NH strength training lowered future hamstring strain injury post-intervention, data showed no significant changes to muscle fascicle length, stiffness, or eccentric hamstring strength occur.\textsuperscript{56} The results of this study compliment these previous data and demonstrate that mechanical variables outside increased strength or muscle length\textsuperscript{56–58} may contribute to muscle strain prevention. Thus, further studies are warranted to determine if the decrease in injury rate related to TNMT is directly associated with changes in muscle stiffness or occurs through other biomechanical modifications.\textsuperscript{9}

Data from this study support past literature that indicates TNMT effectively reduces injury rate and muscle stiffness.\textsuperscript{27,28} Furthermore, the present data demonstrates that the magnitude of response to TNMT varies by sex. Compared to female athletes, hamstring stiffness in males responded less significantly to TNMT at all flexibility orientations. Reduced stiffness response seen in male athletes is exacerbated by a substantially higher risk of hamstring injury and re-injury.\textsuperscript{4,12} Thus, additional study into the utility of injury prevention programs for male athletes may be warranted. More research is needed to determine the cause for sex differences associated with TNMT effectiveness. Future studies may look at TNMT intervention in male and female college athletes who show higher overall hamstring stiffness than their high school counterparts, to elucidate whether the magnitude of hamstring stiffness plays a role in TNMT effectiveness while isolating sex differences.

As with all investigations, the current study had several limitations. The stiffnesses measured by SWE are orders of magnitude lower than the elastic modulus and yield stress for hamstring tissue.\textsuperscript{59} Therefore, we are using hamstring stiffness measurements as a surrogate, as opposed to an absolute measure of hamstring tissue properties. The use of surrogate measures instead of yield stress or elastic modulus may distort the significance of TNMT influence and its relative association with risk of hamstring injury.\textsuperscript{60} Given

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\end{center}
that multiple schools underwent TNMT training simultaneously, a single universal athletic trainer could not be used for this study. This introduces potential variation in facilitation of TNMT intervention, but improved generalizability. To combat any variations in administration of intervention across trainers, all schools implemented the same program, each school trainer was taught by the same interventionalist, and a written protocol was provided. While the population cohort for this study encompassed athletes between ages 13-22 years, data was captured on an insufficient number of athletes aged 15 (n = 3), 19 (n = 9), 20 (n = 5), 21 (n = 8), and 22 (n = 3) to include them as separate groups within the age-based statistical analysis.

In addition, this investigation experienced limitations in the collection of post-season data that accounts for the large number of athletes unable to be tested at follow-up. Post-season data collection was deterred by two events: 1) teams that were assigned to the control group felt a lack of investment in the investigation and subjects were reluctant to return for post-season testing, 2) government mandated shutdowns due to the COVID pandemic prevented the capture of post-season data in Spring 2020. These unfortunate events contributed to substantial attrition in participants in post season data collection, limiting the internal validity of the study. Unfortunately, this limitation was unavoidable, but the captured cohort was deemed acceptable for statistical analysis as each group had a minimum of 21 athletes that completed full analysis. This outbreak also impeded the planned implementation of collegiate TNMT groups for the 2020-2021 basketball season, which resulted in zero collegiate TNMT subjects (Table 1). Lastly, the GE Logiq E9 had a ceiling of SWE of 120 kPa. As hamstring elastic modulus exceeds 2500 kPa, even in a passively flexed state, many SWE stiffness values for the hamstring stiffness were saturated during imaging, which likely increased variability and standard deviations observed in this study. Future studies should incorporate SWE technology with a larger range of measurement for improved precision. Finally, the clinical significance of SWE stiffness measurements remain undescribed. SWE measurements on muscle tissue are reliable within a session but lack precision and offer substantial variability within a whole population, as is herein observed with the standard deviations. Intra-session standard error of the mean for SWE stiffness on lower extremity muscles are between 8-12 kPa, which should be considered when accounting for clinical applicability of statistical findings.

CONCLUSION

Higher SWE measurements have been correlated with increased risk of injury and groups at higher risk of hamstring injury (i.e., males and collegiate athletes). As such, potential exists to utilize SWE stiffness as a surrogate for injury risk; however, further study is necessary to substantiate these claims. Age did not factor into hamstring stiffness or injury. The current findings contradicted previous research citing correlation between increased hamstring injury and decreased stiffness with increased age and may be indicative of a separate trend in adolescent cohorts. Data from this study reiterated that TNMT intervention can lessen muscle stiffness and incidence of re-injury. However, the current data uniquely exhibited that females showed greater response to TNMT, and that intervention effectiveness can be sex specific.

DISCLOSURES

The authors have no financial disclosures or conflicts of interest.

ACKNOWLEDGEMENTS

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REFERENCES


Supplementary Materials

Appendix 1

Sex-Specific Brain Activations during Single-Leg Exercise

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Keywords: neuromuscular control, neuroscience, neuroplasticity, fMRI, Musculoskeletal injuries risk, ACL injury risk

International Journal of Sports Physical Therapy

Background

Females have an increased incidence of musculoskeletal injuries compared to males. Sex differences in neuromuscular control has been widely studied regarding the dynamics and muscle activity during preplanned movements. While muscle activation patterns and movement biomechanics are understood to differ between sexes, it is not well understood how sex influences brain activity for lower extremity movement. Since the brain plays a vital role for voluntary movement and joint stability, it is important to understand the sex differences in brain function in order to better understand neuromuscular control associated with increased musculoskeletal injury risk in female.

Hypothesis/Purpose

The purpose of this study is to understand the differences in brain activation patterns between sexes during a simple active knee extension-flexion movement. It was hypothesized that females would demonstrate higher cortical activation in the somatosensory areas compared to males as a compensatory strategy.

Study Design

Cross-Sectional Study

Methods

Thirteen males and seventeen females who were healthy and physically active participated in this study (Male: 23.7±3.8 years, 74.5±15.5 kg, 172.3±6.4 cm; Female: 20.6±1.6 years, 65.4±12.8 kg, 165±6.1 cm). Functional magnetic resonance imaging data were obtained during a simple left knee extension-flexion exercise with their own leg weight while lying on the MRI table. The blood oxygen level dependent (BOLD) signals were compared between sexes.

Results

There was significantly greater activation in the visual cortices and premotor cortex in females compared to males during the studied movement. Males demonstrated significantly greater activation in the right cerebellum.

Conclusion

The results revealed sex differences in BOLD signal during simple knee extension-flexion movement. The results suggest that sex may be a biological factor in understanding brain activity associated with knee motor control.
Level of Evidence

Level 3

INTRODUCTION

Sex differences related to neuromuscular control have been widely studied due to higher musculoskeletal injuries incident rates, such as anterior cruciate ligament (ACL) injury,\(^1\) ankle instability,\(^2\) and shoulder instability,\(^3\) in females compared to males. Females are two to four times more likely than males to sustain ACL injury when accounting for sport and activity level.\(^4\) Sex differences in anatomical structure, hormones, and neuromuscular control have been described to contribute to ACL injury risk.\(^5\) It has been widely reported that movement biomechanics and associated neuromuscular factors differ between sexes.\(^6\) Females show greater knee valgus,\(^7\) less knee flexion at initial ground contact,\(^8\) less muscle stiffness,\(^9\) and larger quadriiceps activation\(^10\) during jump landing tasks. One of the possible contributors to sex differences in neuromuscular control is proprioception. Proprioception, the sensory information arising from peripheral areas, influences neuromuscular control through its modulation of postural control, joint stability, and conscious sensation.\(^11\) Females are generally known to have diminished proprioception in comparison to males,\(^12\) especially when measured by kinesthesia (one's ability to detect motion and direction).\(^13\) However, the underlying mechanisms responsible for the observed sex differences in movement patterns are poorly understood.

While much of the ACL literature has considered sex as a biological variable influencing dynamic movement and knee neuromuscular control,\(^14\) sex differences have only been documented peripherally using such tools as biomechanical analyses and electromyography.\(^7\) However, less is known about cortical contributions to sex differences for knee motor control. As the brain has an essential role in processing and integrating the sensory signals that arise from the peripheral areas to generate appropriate motor responses,\(^15\) sex differences in cortical activity may play a role in neuromuscular control variability. Neuroimaging techniques provide an avenue to identify brain function during movement to better understand neuromuscular control mechanisms. Functional magnetic resonance imaging (fMRI) is a neuroimaging technique that allows noninvasive measurement of human brain structure and function with high spatial resolution.\(^16\) Over the past few decades, upper limb fine motor control movement tasks have been widely studied with fMRI methods to better understand mechanisms of neuromotor control.\(^17\) However, fewer studies have observed brain function while performing gross lower leg movement tasks due to technical difficulties, including the need to minimize head motion. These studies have examined knee extension-flexion movements,\(^18\) pedaling,\(^19\) and unilateral leg presses,\(^20\) finding that brain regions including sensorimotor area, supplementary motor area, premotor cortex, cerebellum were highly activated during lower extremity movement tasks. Despite this research on brain activation during lower extremity motor tasks, less is known regarding whether males and females have differential cortical activity during lower extremity movements. There is only one previous study examining sex differences in brain activation during isometric ankle dorsiflexion in men and women.\(^21\) While Yoon et al.\(^21\) reported that young men and women have similar cortical activation of motor areas, this was limited to an isometric contraction. It is unknown if any studies have investigated sex differences in brain activity during dynamic knee joint actions. Therefore, the purpose of this study is to understand the differences in brain activation patterns between sexes during a simple active knee extension-flexion movement. Since females are reported to have poorer knee joint proprioception relative to males,\(^12\) it is hypothesized that females would have higher activation in the somatosensory areas as a compensatory strategy to sustain the same knee motor performance.

METHODS

Twelve males and seventeen females age eighteen to twenty-eight, physically active at least two to three times a week, and right-handed/footed were recruited from a university population. Participants participated in running or cutting/pivoting activity as demonstrated on the Marx scale\(^22\) at least once a week. Participants were excluded if they had: a previous history of significant lower leg injuries and surgeries, any neurologic disorders, were currently undergoing a neuromuscular training program or had any contradictions to MRI assessment (any metal or implanted medical device in the body or claustrophobic, etc.). All participants read and signed an informed consent form approved by a University’s Institutional Review Board for the Protection of Human Subjects.

FUNCTIONAL MAGNETIC RESONANCE IMAGING (fMRI)

All MRI data were obtained using a 3T Siemens MRI scanner with a 16-channel head coil (Siemens Tim Trio; Erlangen, Germany). Participants were placed on the MR scanner table headfirst and in a supine position. Head motions generated by lower extremity movement tasks can induce unwanted artifacts that interfere with fMRI data.\(^23\) Therefore, we spent considerable effort to minimize head motion by using a variety of restraints. Participants were stabilized with straps around their hips and chest, then sandbags and multiple sizes of pads were placed around the participant’s head within the head coil to minimize head motion. A mirror was placed on the head coil so that participants were able to see both their own leg and the researchers positioned in the adjacent operator room during the entire MRI scan.
MOBMENT TASK

While obtaining functional MRI data, participants are required to perform knee extension-flexion movement task. A bolster was placed underneath the participant’s leg to allow approximately 45 degrees of knee extension flexion (Figure 1). An ankle immobilizer was positioned on the left ankle to ensure isolated knee extension-flexion movements during the functional imaging tasks (Figure 1). Instruction was given to participants to perform left leg knee extension-flexion movements with a metronome (1.2 Hz) following the auditory cue from the researcher to “start” and “stop”. During the movement task, participants relaxed for 30 seconds then performed 30 seconds of continuous knee extension-flexion exercise of the left leg followed by 30 seconds of relaxation. The participants complete four cycles of movement and relaxation. The auditory metronome was heard by the participant during the entire duration of fMRI scan to control rate of knee extension-flexion movements. The participants performed the task with only the weight of their own limb. There was a familiarization session prior to the scan.

FMRI DATA ACQUISITION

The structural and functional neuroimaging were collected following the methodology of a previous fMRI study by Raisbeck et al. Structural images were initially obtained (repetition time = 2000 ms; echo time = 4.58 ms, matrix field of view = 256 mm; voxel size = 1 mm x 1 mm x 1 mm; scan time=6.5 mins). Then, functional magnetic resonance images were measured to attain the blood oxygen level-dependent (BOLD) signals during knee extension-flexion exercise. Functional image data (fMRI) were obtained (repetition time = 3000 ms; echo time = 28 ms, Flip angle = 78 deg; phase encoding direction = anterior to posterior; matrix field of view = 220 mm; voxel size = 2.5 mm x 2.5 mm x 2.5 mm) during the movement tasks.

FMRI ANALYES

A block design was used for the experimental tasks that include rest and knee movement blocks. It measured 10 full-brain datasets for each 30 seconds block, which resulted in 40 full-brain images for knee extension-flexion movements (4 blocks) and 50 full-brain images for rest (5 blocks); a total of 90 full brain images, congruent with previous work. MRI data were analyzed using the fMRI of the brain (FM-RIB) software library (FSL: The Oxford Centre for Functional MRI of the Brain, Nuffield Department of Clinical Neurosciences, University of Oxford, Oxford, United Kingdom). Standard processing was completed for each subject’s data, including image format converting, reorientation, and brain extraction (using FSL BET).

Then, FEAT (sub-component of the FSL software) was used to perform pre-processing. The pre-process included motion correction (MCFLIRT), interleaved slice timing correction, spatial smoothing at 6 mm full width at half maximum (FWHM), 4D mean intensity normalization. The Independent Component Analysis-based Automatic Removal of Motion Artifacts (ICA-AROMA) was used to remove motion-related noise and increase sensitivity to group-level activation. Then, the first-level analysis was performed for subject-level contrast (rest vs knee movements) using a cluster-based threshold with z threshold at 2.3 and p threshold at 0.05. This process also includes temporal filtering (90s).

Finally, the higher-level analyses were performed with FLAME stage 1-2 using unpaired samples t-test to contrast between sexes (Female > Male; Male > Female) with a z threshold of 2.3 and p<0.05 Gaussian random field cluster corrected. To avoid possible differences in brain structure between sexes that may lead to misinterpretation of functional results, voxel-wise gray matter volumes were included as covariates during the higher-level analysis. Regions of brain activity were identified based on FSL tool atlasyourk with Juelich Histological Atlas, Harvard-Oxford Cortical Structural Atlas, and Cerebellar Atlas in MNI152 space after normalization with FNIRT. Fextquery was used to calculate a mean percentage signal change for each individual’s FEAT results within a cluster mask images from the higher-level analysis.

RESULTS

Demographics of the female and male groups are presented in Table 1. There were no significant differences between sexes in BMI (p=0.77) and Marx (p=0.52) physical activity scales (Table 1). Additionally, there was no significant difference in absolute (p=0.52) and relative (p=0.94) head motion between sexes during the experimental tasks (Table 1).

The fMRI comparisons between sexes are reported in Table 2. During repetitive knee flexion-extension movements, females demonstrated higher BOLD signals in right premotor cortex (p=0.008; Table 2; Figure 2A), the visual cortices right V3, V4 (p=0.011; Table 2; Figure 2B) and Left V1, V2 (p=0.004; Table 2; Figure 2C) Juelich Histological Atlas among the entire brain. The same regions also represent precentral gyrus, lateral occipital cortex, and intracalcarine cortex in the Harvard-Oxford Cortical Structural Atlas. Males demonstrated significantly greater activation in the right cerebellum compared to females with the peak voxel right VIIa and VIIb (p<0.001; Table 2; Figure 2D).
Table 1. Participants’ Demographics and Physical Activity Rating Scale (mean± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Female</th>
<th>Male</th>
<th>p-value</th>
<th>Effect size (Cohen’s d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (year)</td>
<td>20.6±1.6</td>
<td>23.7±3.8</td>
<td>0.004</td>
<td>1.06</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>65.4±12.8</td>
<td>74.5±13.5</td>
<td>0.076</td>
<td>0.69</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>163±6.1</td>
<td>172±6.4</td>
<td>0.000</td>
<td>1.49</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>24.6±4.5</td>
<td>25.1±4.6</td>
<td>0.767</td>
<td>0.11</td>
</tr>
<tr>
<td>Marx Activity</td>
<td>14.0±2.9</td>
<td>15.3±4.2</td>
<td>0.320</td>
<td>0.36</td>
</tr>
<tr>
<td>Absolute Head Motion (mm)</td>
<td>0.39±0.2</td>
<td>0.35±0.1</td>
<td>0.516</td>
<td>0.26</td>
</tr>
<tr>
<td>Relative Head Motion (mm)</td>
<td>0.11±0.1</td>
<td>0.11±0.1</td>
<td>0.935</td>
<td>0.00</td>
</tr>
</tbody>
</table>

DISCUSSION

Given the importance of sex as a biological variable in the study of neuromuscular control, the differences in brain activation between sexes associated with a simple knee flexion-extension task was examined. The results demonstrated that females had greater activation in the premotor cortex and the visual cortices compared to males during a voluntary knee extension-flexion task. Males had significantly greater activation in cerebellum.

PREMOTOR CORTEX

The premotor cortex plays an essential role in the planning or programming of voluntary movements. It has been reported that neurons in the premotor cortex begin firing about 800ms prior to voluntary movement. The premotor cortex also activates when receiving an instruction to move. During the experimental tasks in the current study, participants were given the auditory cues to begin lower limb movements and relax. Higher activation in the premotor cortex in females may indicate that females required greater resources dedicated to the planning of movement for even simple leg extension and flexion movement compared to males.

Activation in the premotor cortex also correlates with increasing complexity of targeted movements, especially the complex sequential movements. The current study movement task is involved with sequential knee extension-flexion exercise with rhythmic timing. Since females typically have a lower hamstring to quadriceps muscular ratio and decreased muscle strength of the lower extremity, potentially indicating a lower capacity for the knee extension-flexion movement task resulting in it being relatively more complex to regulate for females than males.

VISUAL CORTEX

The results also demonstrated that females had significantly higher activation in their visual cortices. The visual cortex has a primary role in visual processing. The visual system is crucial to execute desired physical movements, especially in coordination, regulation, and control of movements. The finding of visual cortex activation was likely related to the ability of participants to see their leg during the tasks through the mirror located on the head coil.
### Table 2. Statistically Significant Regions Contrast between Sexes

<table>
<thead>
<tr>
<th>Atlas</th>
<th>Regions</th>
<th>Voxels</th>
<th>p-value</th>
<th>Z max</th>
<th>Peak MNI Coordinate (mm)</th>
<th>MRI mean(m) Signal Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>F&gt;M</td>
<td>Juelich</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>-92</td>
</tr>
<tr>
<td></td>
<td>R premotor cortex</td>
<td>553</td>
<td>0.008</td>
<td>5.65</td>
<td>2</td>
<td>-92</td>
</tr>
<tr>
<td></td>
<td>R Visual cortex V3, V4</td>
<td>523</td>
<td>0.011</td>
<td>5.38</td>
<td>42</td>
<td>-80</td>
</tr>
<tr>
<td></td>
<td>L Visual cortex V1, V2</td>
<td>408</td>
<td>0.044</td>
<td>4.06</td>
<td>42</td>
<td>0</td>
</tr>
<tr>
<td>M&gt;F</td>
<td>Cerebellar</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>-44</td>
</tr>
<tr>
<td></td>
<td>R cerebellum VIIIa, VIIb</td>
<td>928</td>
<td>0.000</td>
<td>4.18</td>
<td>-2</td>
<td>-44</td>
</tr>
</tbody>
</table>
ever, this activation was significantly higher in females compared to males. Previous work had reported that females demonstrated diminished postural stability compared to males, especially when visual perception was impaired. In addition, females showed decreased proprioception compared to males. This may suggest that females rely more on using visual information in order to execute lower extremity motor tasks, potentially secondary to increased visual cortex activity to generate postural corrective knee movements.

Specifically, the results revealed significantly more activation in visual cortices V1, V2, V3, and V4 in females when compared to males. The primary visual cortex (V1) is the first stage of processing visual information that receives visual input from the retina. The secondary visual cortex (V2) processes visual stimuli and illusory contours. V3 plays a critical role in transmitting visual information, especially processing motion, from the primary visual cortex to parietal and temporal cortices. V4 is interconnected with the higher-order cortex transferring object and spatial visual information.

The Harvard-Oxford Cortical Structural Atlas also reports that subregions in the visual cortex includes the intralcalcarine cortex, lingual gyrus, occipital fusiform gyrus, and lateral occipital cortex. The intralcalcarine cortex and lingual gyrus are a part of the primary visual cortex, and they contribute to the process of visual stimuli. The occipital fusiform gyrus is located in the occipital lobe, and is associated with perceiving body parts and their actions. The lateral occipital cortex is also responsible for visual shape processing. The lingual gyrus also known as the cross-modal cortex has a high capacity for neuroplasticity when experiencing loss of sensory input. Sensory information, including vision, proprioception, and vestibular systems, all have a demonstratable impact on proper motor system function. When proprioceptive information is deficient, vision and vestibular systems may become more highly engaged in order to carry out motor function. Therefore, impaired proprioception in females may alter the cortical function in order to increase neural activity in the visual cortices as a potential compensatory strategy. This compensatory strategy may contribute to females relying more heavily on visual information to perform motor tasks and contribute to sex differences in neuromuscular control. Since the findings suggest that females may rely more on utilizing visual information during physical movement, visual-motor training additions to injury prevention training may be particularly efficacious for females.

CEREBELLM

Males displayed higher cerebellar activation in lobule primarily VIIIa and VIIIb as well as VIIIb and IX of the right cerebellum compared with females. The cerebellum coordinates voluntary movements, motor control, muscular coordination, and executive function. The lobule VIIIa receives projections from the primary motor cortex, and the lobule VIII and VIIIb represent sensorimotor function. With regard to lobule VIIIa and VIIIb function, previous work has demonstrated increased activation of these areas in the upper limb compared to lower limb motion in a female only population. The lobules VIIb and IX are associated with executive functions, including working memory, planning, organizing, and visual divergent thinking. The cerebellum is also engaged with voluntary movement with event timing. O’Reilly et al. showed a significant cerebellum activation during perceptual prediction task when only temporal information (velocity) is involved to predict, but not spatial information (direction). During movement task used in the current study, there was a metronome to assist participants in performing extension-flexion movement with the same timing. Thus, the results of higher activation in the cerebellum in males may indicate that males have a heavier cortico-cerebellar strategy during motor control than females, especially when the task was involved with precise timing. However, the relation to potential injury risk is unknown at this time.

SEX DIFFERENCES IN BRAIN FUNCTION AND STRUCTURE

According to the best-known available data, there is limited research of sex differences in brain activation during lower limb motor tasks. Yoon et al. assessed brain activation patterns in males and females during isometric ankle dorsiflexion with various force control. They discovered that most of the motor cortex areas were activated similarly, with the exception of the right inferior temporal gyrus having greater activity in males at 70% of maximal voluntary isometric contraction. The inferior temporal gyrus plays a primary role in visual stimuli processing, objects recognition as well as biological motion processing. While this previous finding does not support current results, significant differences in task (isometric vs. isotonic), intensity (70% MVIC vs. body weight), and joint (ankle vs. knee) may confound direct comparisons to current work that the visual cortex area was highly activated in females than males.

While sex differences in brain function during lower limb motor control is not well studied, investigations into sex differences during the upper limb fine motor tasks have been reported. Females demonstrated generally higher cortical activation than males during finger tapping tasks. These highly activated regions included the parietal, superior temporal, motor, and somatosensory regions, in addition to the middle occipital cortex. Males displayed higher cortical activation of the caudate nucleus and basal ganglia, as well as the fronto-parietal and temporal regions. Lissek et al. suggested that there may be a different aspect of the motor-related cortical process between sexes. Thus, a sex-specific functional cerebral organization may be used to achieve the same motor skills. Sex differences in brain structure and structural connectivity are also well understood and may contribute to differences in functional activity. Gur et al. found that males have increased white matter size and spinal fluid. Males also have relatively larger cerebrum and ventricle volumes, whereas females were found to have larger overall cortical volumes. Moreover, males reveal higher communication within the hemisphere, and females show higher interhemispheric communication.
measured differently, the previous and current results support the differences in the brain between sexes. Thus, while work is limited in scope, there is support for sex to be considered as a biologic variable when performing research involved in understanding central activation during motor tasks.

The current study results revealed that females showed higher activation in the premotor cortex and visual cortices. This may be due to the fact that females require greater cortical resources to plan and execute motor movement and exhibit less proprioception than males. Furthermore, males demonstrate heavier cortico-cerebellum strategies than females, especially when precise timing is involved with the movement task. These findings may help practitioners and clinicians develop training and rehabilitation methods that improve the efficacy of using visual and sensory information in females. There are a few studies utilizing a visual resource, such as virtual reality system and visual biofeedback to train neuromuscular control in order to induce movement adaption to decrease injury risks.\textsuperscript{53–55} Thus, rehabilitation methods using visual resources may help train female athletes to rapidly pre-plan/program movements in response to changing stimuli, thereby decreasing the risk of injury.

Limitations must be considered when interpreting the current study. There was a relatively low sample size (N=29, male=12; female=17) in this study. In addition, there was a significant age difference between groups (male=22.8±2.2; female=20.6±1.6, p=0.004). However, age was controlled in this study by limiting participants age to between 18-28 years old. Despite well known effects of aging on brain function,\textsuperscript{56} an age difference of just a few years would likely have a minimal effect on the results, thus the impact of the age difference to our results was not a major concern. It is also important to note that the cortical activation differences may not be due to sex differences but instead other factors that may inherently differ by sex (structural differences). To that end, physical activity level was controlled in this study by recruiting only participants who were physically active in order to minimize the impact of confounding variables. In addition, the movement task was standardized to individual’s body size by performing knee flexion-extension movements with participants’ own limb weight.

CONCLUSION

Results of the current study revealed that females have higher neural activation in the premotor cortex and visual cortices compared to males during active knee extension-flexion movements. Males demonstrated significant higher activation in the cerebellum than females. The results, as well as previous work\textsuperscript{17} reporting sex differences in brain activity during motor tasks suggests the need to include sex as a biologic variable in neuroimaging studies involving motor tasks. Understanding sex-specific brain function during an equivalent lower limb motor task may shed further light on sex differences in lower extremity neuromuscular control.

ACKNOWLEDGMENTS

The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. There are no conflicts of interest or funding associated with the present study.

CONFLICT OF INTEREST

The authors declare no significant competing financial, professional or personal interests that might have influenced the presentation of the work described in this manuscript.

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Original Research

Does the 2D Frontal Plane Projection Angle Predict Frontal Plane Knee Moments during Stepping, Landing, and Change of Direction Tasks?

Rachel K Straub, Christopher M Powers

Keywords: 2D video, movement screening, knee biomechanics

Background

Although dynamic knee valgus can be visually identified using the 2D frontal plane projection angle (FPPA), the validity of the FPPA in terms of predicting frontal plane knee kinematics has been questioned. The biomechanical utility of the FPPA may lie in its ability to predict frontal plane knee moments.

Hypothesis/Purpose

The purpose of the current study was to comprehensively evaluate the ability of the FPPA to predict the frontal plane knee kinetics (peak moment, average moment, and moment at peak knee flexion) across a wide range of tasks (stepping, landing, and change of direction).

Design

Crossover Study Design.

Methods

Three-dimensional lower-extremity kinetics and 2D video were obtained from 39 healthy athletes (15 males and 24 females) during execution of six tasks (step down, drop jump, lateral shuffle, deceleration, triple hop, side-step-cut). Linear regression analysis was performed to determine if the 2D FPPA at peak knee flexion predicted frontal plane knee moment variables during the deceleration phase of each task (peak moment, average moment, moment at peak knee flexion).

Results

The FPPA was found to significantly predict the peak frontal plane knee moment for two tasks (deceleration and side-step-cut, $R^2 = 12\% \text{ to } 25\%$), average frontal plane knee moment for five tasks (drop jump, shuffle, deceleration, triple hop, side-step-cut, $R^2 = 15\% \text{ to } 40\%$), and frontal plane knee moment at peak knee flexion for five tasks (drop jump, shuffle, deceleration, triple hop, side-step-cut, $R^2 = 16\% \text{ to } 45\%$).

Conclusion

An increased FPPA (medial knee collapse) predicted increased knee valgus moments (or decreased knee varus moments) during landing and change of direction tasks (but not stepping). However, the predictive ability of the FPPA was weak to moderate.

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INTRODUCTION

The frontal plane projection angle (FPPA) is a two-dimensional (2D) clinical measure that was developed to identify knee valgus during dynamic tasks.\(^1,2\) Although the FPPA has been questioned in terms of being able to predict noncontact ACL injury,\(^3,4\) this measurement has been shown to distinguish between persons with and without patellofemoral pain\(^5-7\) and predict acute lower-extremity injuries (hip, groin, thigh, knee, lower leg, ankle, or foot).\(^8\) Given the potential clinical usefulness of the FPPA, there has been interest in understanding its biomechanical utility in relation to traditional laboratory-based measures of frontal plane knee kinematics.

To date, several studies have compared FPPA measurements and 3D knee kinematics during various tasks. Across studies, the association (R\(^2\)) between the FPPA and 3D knee valgus angle has been reported to range from 0% to 64% across a wide range of tasks (i.e., single limb squat, drop jump, single leg hop, single leg land, lateral jump, and cutting).\(^1,5,9-15\) Although some authors have found that the FPPA and 3D knee valgus are correlated, the reported agreement between these angular measures is poor.\(^16\) More specifically, the FPPA has been shown to overestimate true frontal plane knee motion during a single leg squat,\(^11\) drop jump,\(^10\) and single leg hop,\(^10\) with the 95% limits of agreement ranging from -50\(^\circ\) to 17\(^\circ\),\(^10,11\)

The poor agreement between the FPPA and 3D frontal plane knee valgus can be explained by previous research that has shown that what appears as knee valgus on 2D video actually is a combination of sagittal, frontal, and transverse motions at the hip and knee.\(^5,17,18\) For example, studies have reported that individuals who exhibit poor frontal plane knee alignment based on visual assessment during a step down or single leg squat have increased hip adduction,\(^17\) hip flexion,\(^17\) knee external rotation,\(^17\) and hip internal rotation.\(^18\) Furthermore, an increased FPPA has been found to be correlated with increased hip adduction, knee external rotation, and hip external rotation during a single leg squat.\(^5\)

While it is readily apparent that out-of-plane motions at the hip and knee compromise the ability of the FPPA to accurately represent frontal plane knee kinematics, these frontal and transverse rotations of the thigh and tibia segments may influence variables used to calculate the frontal plane knee joint moment using inverse dynamic equations (e.g., joint center location, joint angular velocities, segment accelerations, etc.). To date, two studies have evaluated the relationship between the FPPA and knee valgus moments with mixed results.\(^12,14\) Herrington et al. reported a strong relationship between the FPPA and peak knee valgus moment during the single leg step down (R\(^2\) = 42%) but not the single leg landing (R\(^2\) = 15%).\(^12\) Similarly, Mizner et al. reported a strong association between the FPPA and knee valgus moment at peak knee flexion during a double-leg drop jump (R\(^2\) = 55%).\(^14\) To date, the ability of the FPPA to predict frontal plane knee moments during tasks that involve pivoting and/or change of direction is not known. This is important as such movements have been shown to result in high knee valgus moments when compared to tasks that are more linear in nature.\(^19\)

The purpose of the current study was to comprehensively evaluate the ability of the FPPA to predict the frontal plane knee kinetics (peak moment, average moment, and moment at peak knee flexion) across a wide range of tasks (stepping, landing, and change of direction). The authors hypothesized that an increased 2D FPPA would be predictive of frontal plane knee moments (i.e., increased knee valgus moments or decreased knee varus moments). Information gained from this study will advance knowledge about the clinical utility of the FPPA in characterizing movement behavior that may expose individuals to lower-extremity injury.

METHODS

PARTICIPANTS

The present study included a sample of 39 healthy athletes from prior studies with different study aims, as previously described.\(^20-22\) Athletes between the ages of 15 and 40 years participated (15 males: age = 23.8 (7.3) yrs., height = 1.81 (0.08) m, mass = 78.9 (16.2) kg; 24 females: age = 17.5 (6.3) yrs., height = 1.65 (0.08) m, mass = 56.1 (11.3) kg). All participants were currently partaking in a sport with high levels of jumping, cutting, or lateral movements (such as soccer, basketball, volleyball, lacrosse, football, netball, or tennis). Participants were excluded if they had current lower-extremity pain, any history of ACL reconstruction, lower-extremity injuries/surgeries in the prior six months or indicated any medical condition that would impair their ability to perform the athletic tasks.

A sample size calculation was performed in G\(^*\)Power (Version 3.1) based on pilot data to determine the number of participants needed to assess the relationship between the FPPA and frontal plane knee moment across six tasks. Using a 5% significance level, 90% power, R\(^2\) value of 0.30 (based on pilot data), and 1 predictor, a minimum of 27 participants was deemed necessary.

INSTRUMENTATION

Three-dimensional and 2D kinematic data were collected at 120 Hz using a video-based 8-camera motion analysis system (Simi Reality Motion Systems GmbH, Unterschleisheim, Germany). One of the eight cameras was positioned 80 cm off the ground (perpendicular to the force plate) and was used to collect the required frontal plane images for the 2D analysis.

Ground reaction forces were collected at 1200 Hz (Model #BP600900-2000, Advanced Mechanical Technology, Inc, Watertown, MA, USA) and synchronized with the motion capture system. The force plate was embedded into the floor and was used for five out of the six tasks evaluated. For the step-down task described below, a portable force plate was integrated into a 22 cm step (Model #O60-7000, Advanced Mechanical Technology, Inc, Watertown, MA, USA).
Table 1. Description of the Tasks Evaluated.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Down</td>
<td>Participants were instructed to lower themselves from a 0.22 m step, tap the opposite heel to the floor, then return to the starting position. This motion was repeated five times without stopping.</td>
</tr>
<tr>
<td>Drop Jump</td>
<td>Participants stood on a 0.46 m box and were instructed to drop from the box, land with only the tested limb on the force plate, then jump as high as possible.</td>
</tr>
<tr>
<td>Lateral Shuffle</td>
<td>Participants were instructed to shuffle to the side as quickly as possible (4.6 m runway), plant only the tested limb on the force plate, then switch directions and shuffle back to the start. This motion was repeated two times without stopping.</td>
</tr>
<tr>
<td>Deceleration</td>
<td>Participants were instructed to run forward as quickly as possible (4.6 m runway), plant only the tested limb on the force plate, then backpedal to the starting position. This motion was repeated two times without stopping.</td>
</tr>
<tr>
<td>Triple Hop</td>
<td>Participants were instructed to perform three consecutive maximal forward hops on the tested limb and stick the landing on the force plate. The starting distance was 90% of the maximal hop length, measured from the center of the force plate. Maximal hop length was established prior to biomechanical testing.</td>
</tr>
<tr>
<td>Side-Step-Cut</td>
<td>Participants were instructed to run forward as quickly as possible (4.6 m runway), plant only the tested limb on the force plate, then turn 90°.</td>
</tr>
</tbody>
</table>

PROCEDURES

Prior to data collection, participants were informed about the nature of the study and written consent was obtained as approved by the Institutional Review Board of the Health Sciences Campus at the University of Southern California. Once informed consent was obtained, participants warmed up on a stationary bike for 5–10 minutes. For all data procedures outlined below, data were obtained on the right limb.

Participants were instrumented with 17 reflective markers (10 mm diameter) on the right lower extremity, as previously described. Two-dimensional video and 3D motion analysis were collected during the following tasks: 1) Step Down, 2) Drop Jump, 3) Lateral Shuffle, 4) Deceleration, 5) Triple Hop, and 6) Side-Step-Cut. Details regarding the instructions provided to participants for each of the tasks can be found in Table 1. These tasks were selected based on current knowledge of movements thought to be associated with various sport injuries. A trial was considered successful if all markers remained visible and only the foot of tested limb fully contacted the force plate. Participants were permitted to practice until comfortable with the performance of each task. One to two trials were obtained for each of the tasks.

DATA ANALYSIS

The first successful trial was selected for each task and used for data analysis. Marker position data were labeled in Simi Motion and then exported with the force data to Visual3D software (C-Motion, Inc, Germantown, MD, USA). Marker trajectory and analog force plate data were low-pass filtered at 12 Hz, using a fourth-order Butterworth filter. Joint angles were calculated using a X-Y-Z (sagittal-frontal-transverse) Cardan sequence.

Inverse dynamics equations were used to calculate net joint moments (external) at the knee. Moment data were normalized to body mass and height. Three frontal plane knee moment variables were extracted (peak moment, average moment, and moment at peak knee flexion). The peak and average frontal plane knee moments were calculated during the deceleration phase of all tasks (initial contact to peak knee flexion). In addition, the frontal plane knee moment at peak knee flexion was identified. For the step down, the peak and average frontal plane knee moments were calculated during the lowering phase (initiation of the movement to the time at which the heel touched the ground). For calculation of the peak moment for trials in which a valgus moment was not present, the minimum varus moment was identified and used for statistical analysis.

For the 2D video analysis, the image containing peak knee flexion was identified. For the step down, the image at which the contralateral heel touched the ground was used for analysis. Images were uploaded into ImageJ software (Version 1.50i, National Institute of Health, USA) for 2D angle assessments. The FPMA was measured as the angle formed by three points (ASIS, knee joint center, ankle joint center). This value was subtracted from 180 to represent the anatomical frontal plane alignment of the knee. A positive value represented knee valgus (knee joint center medial to a line formed from the ankle and ASIS) and a negative represented knee varus (knee joint marker lateral to a line formed from the ankle and ASIS) (Figure 1). All 2D measurements were obtained by a single investigator who demonstrated excellent intra-rater reliability for all tasks prior to the start of the study (ICCs ranging from 0.91 to 1.0).

STATISTICAL ANALYSIS

Linear regression analysis was used to assess the ability of the 2D FPMA angle (independent variable) to predict the frontal plane knee moment (dependent variable). This analysis was repeated for each task and was run separately for each dependent variable (peak frontal plane knee moment, average frontal plane knee moment, and frontal plane knee moment at peak knee flexion). R² values were interpreted as strong (≥0.50), moderate (0.25–0.49), weak (0.10–0.24), and negligible (0.0–0.09). All statistical analyses were performed using SPSS Version 27 (Chicago, Illinois, USA) and a custom MATLAB script (The Mathworks, Inc., Natick, MA) with alpha set at 0.05.
RESULTS

Due to technical issues with the force plate, ground reaction force data were not available for one subject during the drop jump and eight participants during the step-down task. Descriptive statistics for the FPPA, peak frontal plane knee moment, and average frontal plane knee moment for each task are presented in Figure 2. Time series data for the frontal plane knee moment are presented in Figure 3.

RELATIONSHIP BETWEEN FPPA AND PEAK FRONTAL PLANE KNEE MOMENT

The FPPA was found to significantly predict the peak frontal plane knee moment for deceleration ($R^2 = 0.12, p = 0.032$) and side-step-cut ($R^2 = 0.25, p = 0.001$), with a larger FPPA predicting increased knee valgus moments (or decreased knee varus moments). However, the FPPA did not predict the peak frontal plane knee moment for step down, drop jump, lateral shuffle, and triple hop (Figure 4).

RELATIONSHIP BETWEEN FPPA AND AVERAGE FRONTAL PLANE KNEE MOMENT

The FPPA was found to significantly predict the average frontal plane knee moment for drop jump ($R^2 = 0.25, p = 0.001$), shuffle ($R^2 = 0.40, p < 0.001$), deceleration ($R^2 = 0.20, p = 0.004$), triple hop ($R^2 = 0.15, p = 0.015$), and side-step-cut ($R^2 = 0.51, p < 0.001$), with a larger FPPA predicting increased knee valgus moments (or decreased knee varus moments). However, the FPPA did not predict the average frontal plane knee moment for step down ($R^2 = 0.0, p = 0.775$) (Figure 5).

RELATIONSHIP BETWEEN FPPA AND FRONTAL PLANE KNEE MOMENT AT PEAK KNEE FLEXION

The FPPA was found to significantly predict the frontal plane knee moment at peak knee flexion for drop jump ($R^2 = 0.39, p < 0.001$), shuffle ($R^2 = 0.45, p < 0.001$), deceleration ($R^2 = 0.16, p = 0.015$), triple hop ($R^2 = 0.17, p = 0.008$), and side-step-cut ($R^2 = 0.27, p < 0.001$), with a larger FPPA predicting increased knee valgus moments (or decreased knee varus moments). However, the FPPA did not predict the frontal plane knee moment at peak knee flexion for step down ($R^2 = 0.02, p = 0.41$) (Figure 6).

Figure 1. Measurement of the FPPA obtained at peak knee flexion from 2D video. Positive values indicate knee valgus.

Figure 2. Average FPPA and moment variables for the six tasks evaluated. Error bars represent one SD.

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Figure 3. Time-normalized frontal plane knee moment data for the six tasks evaluated. Error bars represent 1 SD. Positive values represent knee valgus moments.
Figure 4. Linear regression models to predict the peak frontal plane knee moment for each task.
Figure 5. Linear regression models to predict the average frontal plane knee moment for each task.
Figure 6. Linear regression models to predict the frontal plane knee moment at maximum knee flexion for each task.
DISCUSSION

The purpose of the current study was to comprehensively evaluate the ability of the FPPA to predict the frontal plane knee kinetics (peak moment, average moment, and moment at peak knee flexion) across a wide range of tasks (stepping, landing, and change of direction). In general, the FPPA was a better predictor of the average frontal plane knee moment (five out of six tasks) and frontal plane knee moment at peak knee flexion (5 of 6 tasks) compared to the peak frontal plane knee moment (two out of six tasks). For all significant models, an increased FPPA predicted increased knee valgus moments (or decreased knee varus moments) during landing and change of direction tasks (but not stepping). However, the strength of the predictive models was weak to moderate \((R^2 = 12\% \text{ to } 45\%)\), highlighting that the utility of the FPPA as an indicator of frontal plane knee moments during landing and change of direction tasks is limited.

The current results are in general agreement with the findings of Herrington et al.,\(^{12}\) and Mizner et al.,\(^{14}\) both of whom examined the ability of the FPPA to predict knee valgus moments during various tasks. Mizner et al. reported that an increased FPPA predicted the knee valgus moment at peak knee flexion during a drop jump task \((R^2 = 55\%)\),\(^{14}\) which is comparable to our moment results at peak knee flexion for the drop jump \((R^2 = 59\%)\). Herrington et al. reported that an increased FPPA did not predict the peak knee valgus moment during a single leg landing from a box \((R^2 = 13\%)\),\(^{12}\) which agrees with our finding for the peak frontal plane knee moment during the triple hop \((R^2 = 2\%)\). However, Herrington et al. reported that an increased FPPA predicted the peak knee valgus moment during a single leg squat \((R^2 = 42\%)\),\(^{12}\) which is in contrast with our findings for the step down for the peak frontal plane knee moment \((R^2 = 1\%)\). However, the step down and single leg squat differ in a number of kinematic variables,\(^{23}\) which makes direct comparisons difficult.

Across tasks, the highest \(R^2\) values were found for the average frontal knee moments and frontal plane knee moments at maximum knee flexion. Given that the FPPA was measured at peak knee flexion, it is logical that the FPPA was predictive of the frontal plane knee moment at that point in time. Additionally, the fact that peak knee flexion was used to indicate the end of the deceleration phase for each task may explain why the FPPA predictive models for the average moment during the deceleration phase were similar to those observed for the frontal plane knee moment at peak knee flexion. The ability of the FPPA to predict the peak frontal plane knee moment was limited to two of the six tasks (deceleration and cutting), with \(R^2\) values being lower than the other two variables examined. The limited ability of the FPPA to predict the peak frontal plane knee moments may be explained by the fact that the peak moment did not always occur at the same time point at which the FPPA was measured (Figure 3). As such, the timing of the kinetic variables of interest should be considered when measuring the FPPA at a single point in time.

With respect to the strength of the predictions across tasks, the step down exhibited non-significant results for all three frontal plane knee moment variables \((R^2 = 0-2\%)\) (Figure 4-6). This finding may be related to the fact that 100% of participants exhibited average knee varus moments during this movement, and this task had the lowest average frontal plane knee moment (Figure 2, Figure 5). In contrast, the strongest significant relationship was observed for the shuffle task, which had the second highest average frontal plane knee moment and a relatively large prevalence of average knee valgus moments \((69\%\) of participants) (Figure 2, Figure 5). It appears that the FPPA may be a stronger predictor of frontal plane knee kinetics when a knee valgus moment is present, with the strength of the predictability contingent on the observed frequency and magnitude of knee valgus moments. This is logical as the FPPA is indicative of inward collapse of the knee and therefore would be expected to be indicative of the variables that would be related to a knee valgus moment (i.e., medial positioning of the knee joint center, etc.).

Previous studies have reported that the FPPA is an inconsistent predictor of frontal plane knee kinematics\(^{1,5,9-15}\) and that the general agreement between 2D and 3D frontal plane knee angles is poor.\(^{16}\) Based on the current study and the work of previous authors who have evaluated the ability of the FPPA to predict frontal plane knee moments,\(^{12,14}\) it appears that the FPPA may be a better indicator of knee kinetics as opposed to knee kinematics. It is possible that the clinical utility of the FPPA as a predictor of injury\(^{8,26}\) or the ability of the FPPA to differentiate between healthy and clinical populations\(^{3-7}\) may lie in the fact that this measure is a predictor of frontal plane knee moments. An argument could be made that the frontal plane knee moment is more suggestive of knee loading as opposed to frontal plane knee motion.

Regarding clinical application, the current results suggest that obtaining measures of the FPPA from hand-held mobile devices (i.e., phones, tablets, etc.) may be of value. However, it is important to note that the 2D video data obtained in the current study were captured from a fixed camera that was aligned perpendicular to the force plate. As with all measurements obtained from 2D video, there is potential for parallax error owing to the camera being positioned at an angle to the patient. Such error would influence the measurement of the FPPA and the ability to infer frontal plane knee moments as described in the current study.

There are several limitations within the current study that warrant discussion. First, these data were obtained from healthy individuals. As such, our results may not be applicable to those with specific knee conditions (i.e., patellofemoral pain, ACL injury, etc.). Second, only the deceleration or lowering phase of each task was considered in our moment analysis. Therefore, our results may not apply to the acceleration phase of the tasks evaluated. Third, the current study was cross-sectional in nature. The current results cannot be interpreted to suggest that increased FPPA angles are predictive of knee injury. Lastly, for all regression models, only a single predictor (FPPA) was examined.
The $R^2$ values reported could be improved by including other 2D measurements such as frontal plane motion at the hip, pelvis, or trunk.\textsuperscript{27}

\textbf{CONCLUSION}

In summary, the results of the current study suggest that the FPPA is a predictor of frontal plane knee loading during landing and change in direction tasks, specifically when the frontal plane knee moment is calculated as the average moment or the moment at peak knee flexion. For all significant models, an increased FPPA (indicative of medial knee collapse) predicted increased knee valgus moments (or decreased knee varus moments) during landing and change of direction tasks (but not stepping). However, the ability of the FPPA to predict frontal plane knee kinetics appears to be task dependent, with the strength of the prediction improved with increased frequency and magnitude of observed knee valgus moments. In addition, the strength of the prediction was weak to moderate, highlighting that the validity of the FPPA as a predictor of frontal plane knee moments during landing and change of direction tasks is limited.

\textbf{CONFLICTS OF INTEREST}

The authors have no conflicts of interest to disclose.

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Lower Extremity Kinematic Waveform Analysis During a Single Leg Drop Task – Including a Single Subject Design

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Keywords: Drop Landing, Single Subjects, Statistical Parametric Mapping, Lower Limb Asymmetry

BACKGROUND
Lower limb asymmetries may be associated with increased injury risk in an active female population. However, an appropriate method for determining these asymmetries has not been established.

HYPOTHESIS/PURPOSE
The purpose of the present study was to examine the single leg drop landing (SLD) kinematic waveforms of female recreational athletes for the pelvis, hip, and knee using statistical parametric mapping (SPM). It was hypothesized that individual bilateral differences would be masked by the group analysis.

STUDY DESIGN
Descriptive Laboratory Study.

METHODS
The current study examined the sagittal and frontal plane pelvis, hip, and knee kinematics of nine physically active females during a SLD. To better elucidate whether asymmetries were present between right and left limbs throughout the landing phase, data were analyzed with SPM. The time-series data were comprised from initial contact to the bottom of the landing. A single subject design was also included to account for potential interindividual variability.

RESULTS
At the group level there were no statistical differences between the right and left limbs of participants for all variables. The single subject design yielded at least two significant asymmetries for all participants. Six out of the nine participants had bilateral differences for all six kinematic time-series.

CONCLUSIONS
The lack of significant differences at the group level may have been masked by movement variability amongst participants. For example, when considering participants with significant differences for hip flexion, four participants had greater values on the left limb and three on the right. A similar observation was made for knee flexion where three participants had significantly greater kinematic values on the left versus four on the right. Until a method is developed to adequately dichotomize lower extremities during the SLD task, a single subject design strategy be used with group analysis when making bilateral comparisons.

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LEVEL OF EVIDENCE

INTRODUCTION

Landing on a single leg is a common movement in sports such as basketball, volleyball, and soccer. When this movement is not adequately controlled by the neuromuscular system, non-contact anterior cruciate ligament (ACL) injury may occur. It is well established that female athletes are more likely to suffer non-contact ACL injuries than male counterparts participating in the same sports. Female athletes have also been shown to have an increased propensity to experience ACL injury on their non-dominant limb which was defined as the stance limb when kicking a ball. However, minimal differences in mechanical variables have been reported between dominant and non-dominant limbs during a cutting task in female soccer athletes. Thus, it is unclear whether the reported increase in injury rate between dominant and non-dominant limbs are linked to bilateral mechanical differences.

Mechanisms for non-contact ACL injury consist of dynamic joint angles that result in excessive tensile forces on the ligament. For example, excessive knee abduction, and internal rotation have been shown to increase ACL strain during cadaveric modeling. Video analysis of ACL injury incidents has identified combined knee abduction and internal rotation as a mechanism of injury. Investigators have also demonstrated an increased lateral pelvic tilt is related to increased knee abduction moments, which may increase the risk of non-contact ACL injury. Alternatively, studies using 3D modeling and magnetic resonance imaging suggest that the ACL is under greatest strain during knee extension during dynamic and static loading. In addition to the various mechanisms of ACL injury, researchers have also hypothesized that lower extremity kinematic differences (asymmetry) can increase the risk for injury due to an increased loading and reliance on one limb, combined with an inability to maintain stability on the other.

The single leg drop-landing (SLD) task is often used to assess lower limb kinematic symmetry. Other tasks that are more functionally related to sport movements, including cutting maneuvers, single leg hop for distance, and single leg jumps, have also been used to analyze lower limb symmetry. However, these tasks may require greater coordination and training to achieve or perform within the limits of a study design. Thus, the relatively limited complexity of the SLD may make it advantageous for the analysis of intrinsic bilateral asymmetries across individuals with varied training backgrounds.

Previous studies that have used a SLD task to examine potential bilateral lower extremity asymmetries have reported mixed results. Recently, Wang and Fu demonstrated an increased total hip and knee range of motion in the sagittal plane in the dominant limb of female soccer players. Other researchers did not find bilateral kinematic hip and knee differences in recreationally active females. The differences between populations may explain the conflicting findings. However, another possible reason for the discrepancies between these studies is the classification of lower extremities by either dominant limb or non-dominant limb when performing a group analysis.

When using a group analysis for the examination of bilateral differences, problems may arise from the difficulty of classifying a dominant lower limb. While several studies have defined the dominant lower limb as the limb used to kick a ball, limb dominance may be task-specific. If limb dominance is task-specific, grouping participants’ limbs based on what would be an arbitrary question, may generate misleading results. These factors have led researchers to contend that single subject design data should be reported in addition to group analysis when making bilateral comparisons. Thus, reducing the potential for applicable findings to be masked by interindividual variability between dominant or non-dominant limbs.

Another potential reason for discrepancies between the aforementioned studies is the interpretation of variables at discrete time points which may lead to analysis of less than 5% of the data. Discrete analysis of biomechanical variables may not always be comparable across participants or within participants due to temporal variations in movement traces. These potential inconsistencies may limit the interpretation of a temporal component, and how kinematics temporally relate to other biomechanical factors within the same movement. Thus, a more robust method may be required when examining a movement related to ACL injury risk that does not have a clear mechanism and timing. A proposed solution to this problem is statistical parametric mapping (SPM) which can be used to statistically analyze the kinematic waveform of the complete task cycle.

Bilateral asymmetries during a SLD have not been analyzed with a SPM analysis at the group or single subject level. Thus, the purpose of the present study was to examine the SLD kinematic waveforms of female recreational athletes for the pelvis, hip, and knee using SPM. By including a group analysis and single subject design, the current study sought to identify the potential of inter-participant variability to influence group bilateral asymmetries. It was hypothesized that bilateral differences of the waveforms at the single subject design level would occur but not at the group level due to inter-participant variability.

METHODS

PARTICIPANTS

Nine female participants who were free from lower limb surgery, disease, or current injury volunteered for this study. Participants had a mean [SD] age of 22.4 [3.5] years, height of 1.68 [0.57] m, mass of 61.0 [6.7] kg. All participants were defined as physically active and performed plyometric activities at least once per week. Physically active was defined as performing at least 30 minutes of low-in-
tensity exercise five times per week, 20 minutes of high-intensity exercise three times per week, or participants who ran at least five miles per week. For descriptive purposes, all participants were asked which limb they preferred to kick a ball with. All reported that their right limb was their preferred kicking limb. Prior to participation, all participants signed an informed consent form approved by the University’s internal review board.

INSTRUMENTATION

Three-dimensional marker trajectories were collected with an eight-camera motion capture system (250 Hz; VICON, Oxford Metric Ltd., Oxford, UK). Participants were equipped with 73 retro-reflective markers (14mm) used to create a custom cluster-based model for the upper extremities, torso, pelvis, and lower extremities (Figure 1).

A force-platform (1000 Hz; ORG-6, AMTI Inc., Watertown, MA, USA) time synchronized with the motion capture system was used to collect ground reaction forces (GRFs).

DROP LANDING PROCEDURE

Prior to performing the SLD, participants performed a five-minute warm-up on a stationary bicycle. Participants were then asked to perform the SLD task from a 60 cm platform after completing two practice trials on each leg. The platform was positioned behind the force platform with a minimum distance that allowed participants to vertically land on the center of the force platform to minimize GRF in the anteroposterior direction. Participants were asked to place the limb they would land on off the step and then drop down onto the force plate with minimal assistance from their stance limb to drop off the box. No restrictions were placed on the positioning of the arms. Participants performed 10 successful trials on each leg with a maximum of 15 attempts. Participants were given as much time as they needed between trials and the starting limbs were counterbalanced to reduce the potential effect of fatigue. Trials were considered successful if the participant was able to drop off the box without lowering themselves with the stance leg and maintain balance upon landing as determined by the researcher. All participants wore their own activity shoes, which was done to remove any perturbation caused by novel footwear.

DATA ANALYSIS

Angular kinematics and center of mass were computed using a Cardan (X-Y-Z) rotation sequence with Visual 3D software (v6, C-Motion Inc., Germantown, MD, USA). Pelvis segment angles were calculated using a Z-Y-X sequence of rotations to be consistent with the conventional clinical understanding of pelvic tilt and pelvic drop. The pelvis was modeled as a using the anterior and posterior superior iliac spines and pelvis segment angles were calculated relative to the global coordinate system. Pelvic drop was defined as the angle in the frontal plane and pelvic tilt was defined as the segment’s rotation in the sagittal plane. Negative values in the frontal plane were represented as a contralateral pelvic drop and anterior pelvic tilt was represented by positive values. Marker trajectories were filtered using a fourth-order Butterworth filter at 8 Hz and kinetic data were filtered at 20 Hz respectively. Vertical GRF data was used to define initial contact (IC) at the beginning of the deceleration phase. The IC was defined as the moment when the vertical GRF threshold of 20 N was surpassed. To define the end of the deceleration phase, we used the minimum ver-
ticle height of the center of mass (minCOM).26 Joint (hip and knee) and segment (pelvis) temporal data were analyzed between IC and minCOM using MATLAB (MathWorks, Natick, MA, USA). Temporal data were interpolated to 101 data points (100% of cycle) for the SPM analysis.

STATISTICAL PARAMETRIC MAPPING

All SPM analyses were conducted in MATLAB using an open-source software package spm1D 0.4.27 Multiple paired t-tests (p < 0.05) were performed with Bonferroni corrections to compare the grouped kinematic data of lower extremity limbs for all participants at each percentage of the cycle. For group analysis the mean trajectories of each participant’s twenty trials (10 on each leg) were used. Additionally, paired t-tests were performed comparing the limbs for each individual participant that was calculated using 10 trials from each limb. The significance level for all statistical tests after the alpha corrections was (p = 0.006). The null hypothesis was rejected if the computed t-value exceeded the critical threshold. In SPM the t-value is calculated across the temporal region of interest (i.e., IC to minCOM). Whereas, the critical threshold is a product of random field theory that can be used to determine a threshold where equivalently smooth Gaussian random fields would cross at the specified alpha level when the null hypothesis is true.28

RESULTS

The group SPM analysis with paired t-tests did not reveal any significant differences between the dominant and non-dominant limbs for all kinematic variables (Figure 2).

Individual SPM analysis with paired t-tests revealed significant kinematic differences between the right and left limbs for all participants. At the hip in the sagittal plane, seven participants had a significant difference between their two limbs. During the phase when the difference between lower limbs exceeded the critical threshold, four of those seven participants had a relative increase in hip flexion on the right limb (Figure 3).

Conversely, the remaining three with significant differences were shown to have increased hip flexion on their left limb. At the knee in the sagittal plane, seven participants had a significant relative difference between their two limbs (Figure 4).

Four of those participants increased knee flexion on the left limb and three increased knee flexion on the right limb. Anterior pelvic tilt was greater when landing on the left limb in five participants, and in three participants when landing on their right limb (Figure 5).

For frontal plane hip motion, six participants had increased hip adduction on the right limb and three participants had relatively increased adduction on the left limb (Figure 6).

At the knee, two participants had increased knee abduction on the right limb, 4 had relative increases on the left limb, and participants six and eight had relative differences between limbs in both directions (Figure 7).

Significant differences for pelvic drop occurred in eight of the nine participants (Figure 8).

Six of those participants had a relative decrease in pelvic drop when landing on their right limb.

DISCUSSION

The aim of this study was to examine physically active females for potential bilateral differences in pelvis, hip, and knee kinematics during a SLD task. A group analysis (comparison of mean data between right and left limbs) and a single subject design was used to ascertain the findings of potential bilateral differences among the population studied. The findings indicated that there were no significant differences for kinematic variables between the right and left limbs when analyzed at a group level. However, this was not indicative that bilateral differences were not prevalent among the study’s population. For instance, each of
The participants demonstrated at least two asymmetries out of the six variables in question and six out of the nine participants had bilateral differences for all kinematic time-series. Thus, the hypothesis that bilateral differences would be observed at the single subject design level, but not at the group level was accepted. The consequence of group analysis concealing individual differences is not novel to the current study.29–31

The data were grouped by right and left limbs because there is currently not a clear metric for determining limb dominance during a SLD task. However, the selection of comparing right and left limbs was not an adequate method for homogenizing participant data to describe the observed differences between limbs. Therefore, the approach of including a single subject design allowed us to look at bilateral differences without defining the criteria of which leg was dominant during the task. It should be noted that all participants reported that they preferred kicking a ball with their right limb. Thus, grouping limbs by this metric would not have affected the outcome of the data.

The absence of significant group findings may be explained by not all participants displaying similar movement patterns with their right or left limb. For example, participants (4, 5, 9) had a significant relative increase for hip flexion angles on their right limbs when compared to their left (Figure 3). Conversely, participants (1, 2, 6, 8) demonstrated greater hip flexion on their left limb (Figure 3). Similar participant variability was also observed in the other variables of interest. Thus, it appears that in this sample population of uninjured participants, the heterogeneous movement patterns influenced the findings at a group level and provided support for the use of single subject analysis.

The current study’s group findings in recreational female athletes are similar with those of Wang and Fu21 who found no bilateral differences in female soccer players at IC. However, the researchers15 did not include a single subject design which may have limited their interpretation of their results. For instance, when considering this study, four of the participants (1, 4, 6, 9) had a significant difference for hip and knee flexion at IC (Figure 3, 4). Interestingly, for hip frontal plane motion all but one of the participants (8) demonstrated a significant difference at IC (Figure 6). At the knee in the frontal plane, all but two of the participants (4, 8) had statistically similar waveforms at IC (Figure 7). Another difference between the two studies methods is the fact that the female soccer players dropped from a box 20cm shorter than what was used for the current study’s participants (60cm).

It has been shown that increasing the height of the SLD task may result in greater bilateral kinematic differences.16 In a study where participants landed from the same height for the SLD task as the current study, the researchers16 also reported that no bilateral differences were observed for hip and knee flexion between the limbs of recreationally active females. However, the researchers16 analyzed the kinematic data at the moment of peak vertical GRF because it was thought to be related to the timing of injury. As discrete time points were not considered in the current analy-

Figure 3. Hip sagittal plane kinematics for each participant from initial contact to the minimum height of the center of mass.

Positive values indicate hip flexion. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.
Figure 4. Knee sagittal plane kinematics for each participant from initial contact to the minimum height of the center of mass. Positive values indicate knee flexion. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.

Figure 5. Pelvis sagittal plane kinematics for each participant from initial contact to the minimum height of the center of mass. Positive values indicate anterior pelvic tilt. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.
sis (other than to determine the beginning and end of the movement) it is difficult to draw comparisons with their kinematic data. The discrepancies between cadaveric and model simulated ACL strain is conflicting for researchers looking to identify the optimal time or joint angle for assessing risky lower extremity movement patterns. Research from cadaveric modeling has been used to suggest that peak ACL strain occurs simultaneously with peak knee abduction angles. Thus, there is a potential advantage of using a wave form analysis technique as it limits the bias of researchers when selecting discrete time points for analysis.

To the best of the authors’ knowledge, this is the first study to include pelvic kinematics with bilateral comparison during a SLD task in females. Bilateral pelvic imbalances may be relevant to injury prevention as increased pelvic kinematics have been shown to result in amplified torque at the knee in the frontal plane during a SLD jump. Only three of the participants displayed mean pelvic drop angles below 0° (neutral). However, these findings may be more indicative of the SLD methods than the ability of the participants to stabilize their pelvis in the frontal plane. For example, each of the participants landed with a negative pelvic drop (i.e., their hip on their landing limb was lower). This is likely due to asking them to step off the box with the same limb that they landed on. If the participants had landed in a more neutral position, greater pelvic drop angles may have been observed. Nonetheless, all but one of the participants demonstrated a bilateral difference. Interestingly, six of the participants (1, 2, 3, 5, 7, 9) who landed in a more neutral pelvic position (closer to 0°) had increased knee abduction angles on the same limb (Figure 7, 8). This suggests that pelvic and knee kinematics may be linked during a SLD task. However, a causative relationship cannot be established with the current evidence.

When examining anterior pelvic tilt, most of the participants (3-9) demonstrated a significant bilateral difference. Although the purpose of the current study was not to describe the ideal anterior pelvic tilt during the movement task, it may be that not all participants with bilateral differences possess inadequate pelvic control. For instance, participants 7, 8, and 9 either maintained a relatively neutral pelvis, or decreased the amount of pelvic tilt throughout the motion (Figure 5). In contrast, participants 1 and 2 did not present with bilateral differences but increased their degree of anterior pelvic tilt from initial contact to the end of the movement.

Although the results of this single subject analysis indicated that each of the participants had kinematic imbalances during the SLD task, it is still unclear whether these asymmetries were suggestive of poor movement patterns (on one or both limbs) that may facilitate an increased risk of injury. It may be that the observed bilateral differences were simply a result of performance variability between the two limbs. In short, performance variability is a natural biologic phenomenon that adapts for desired outcomes based on force distribution mechanisms, development or skill level, and environmental factors. Inter-indi-
Individual variability has been shown to occur in professional athletes during basketball shooting and elite javelin throwers,\textsuperscript{30} as well as in recreational athletes while running and performing a SLD.\textsuperscript{23,30} The participants’ bilateral kinematic differences in the current study may have been compensations that occurred due to muscular strength imbalances, prior training, or possibly structural/anatomical asymmetries. Thus, the observed imbalances may have been necessary to complete the task. Further research is needed to examine the circumstances in which movement compensations and bilateral differences are beneficial or detrimental.

This study has several limitations. First, the current study only collected data on a small sample of physically active female participants. Group findings may have been apparent if participants had more homogeneous training backgrounds. A larger sample size may also have provided a greater probability of observing differences at the group level. Second, participants were only stratified based on their right or left limb. Future research might examine the potential for task specific methods to dichotomize limbs. For example, participants may self-identify their preferred landing limb. Lastly, due to the method participants dropped off the box (i.e., stepping), there may have been differences in the distance they fell onto the force plate, either between legs, or participants.

CONCLUSION

At the single subject analysis level, participants were asymmetrical regarding their kinematic time-series. However, these differences were not observed in any of the waveforms for the group analysis. The authors recommend that until an accepted method for dichotomizing right and left limbs for bilateral comparisons is accepted, single subject design should be included with any group analysis where bilateral differences are examined.

DISCLOSURES

This study was approved by the University of Idaho Institutional Review Board, irb@uidaho.edu

The authors did not have any financial or personal relationships with people or organizations that may have inappropriately influenced or biased their work.

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Figure 8. Pelvic frontal plane kinematics for each participant from initial contact to the minimum height of the center of mass.
Positive values indicate pelvic drop. Mean values are represented by dashed lines with the solid lines indicating standard deviations. The right limb is shown as black, and the left shown as red. Shaded areas represent significant differences as determined from the statistical parametric mapping.
REFERENCES


Movement Competency Screen: Rethinking the Rating

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Keywords: movement competency, dance, athlete, pre-season screening, musculoskeletal disorder

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Background
Dancers are at high risk of musculoskeletal disorders. There has been a growing interest in the last few years in pre-season screening using tools to evaluate movement competency, among which is the Movement Competency Screen (MCS). It is currently scored using a categorical 3-level rating system, but this method does not seem to take into account the load level of movements. A 5-level scoring system could potentially alleviate this problem.

Hypothesis/Purpose
For each scoring system, to investigate (1) the internal consistency, and (2) the association with transversus abdominis activation (TrA), hip muscle strength and with Functional Movement screen (FMSTM) total score.

Study design
Secondary analyses of a prospective cohort study.

Methods
One hundred and eighteen professional and preprofessional dancers evolving in ballet or contemporary dance were recruited. The MCS was performed and was scored according to the 3- and 5-level scoring systems. The key variables for movement competency that were considered for convergent validity were the activation ratio of the TrA evaluated with ultrasound imaging and hip strength assessed with a handheld dynamometer. Movement competency was also measured with the FMSTM.

Results
Internal consistency was higher for the 5-level scoring of the MCS items (α=0.548) compared to the 3-level scoring system (α=0.494). Multiple linear regressions showed that TrA activation, hip adductor strength, and FMSTM could significantly explain 24.0% of the variance for the 5-level scoring system of the MCS whereas hip internal rotator strength and FMSTM could explain only 16.4% of the variance for the 3-level scoring system.

Conclusion
The 5-level scoring system showed better metrologic properties in terms of internal consistency and concurrent validity and therefore, should be preferred over the 3-level scoring system in future research.
Level of Evidence

Level III

BACKGROUND

Musculoskeletal injuries among dancers represent a major concern.\(^1\)\(^-\)\(^4\) In addition to being associated with serious physical and psychological disabilities in athletes, injuries can represent an extensive financial burden on health care systems.\(^5\) In order to better understand the underlying pathokinesiology of non-traumatic injuries among dancers, researchers have focused on specific, segmental impairments identified as potential risk factors in other athlete populations.\(^6\)\(^-\)\(^8\) These risk factors include lower or delayed activation of the transversus abdominis muscle (TrA),\(^6\)\(^-\)\(^8\) as well as reduced hip and knee muscle strength.\(^9\) However, with prevention of injuries in mind, there has been a continued interest in the evaluation of movement competency in recent years, as opposed to specific segmental impairments assessments.\(^10\) This shift in approach has given rise to the development of movement competency screening tools.\(^11\)\(^-\)\(^14\) Movement competency can be defined as the ability to achieve fundamental movements without any functional deficits.\(^15\) Strength and motor control are key to preventing faulty movement patterns. For instance, the activation of the TrA and having stronger lower limb muscles have been linked to movement competency.\(^16\) The evaluation of movement competency using screening tools has enabled the identification of athletes and workers at risk of injuries.\(^17\)\(^,\)\(^18\)

Among the multiple movement competency screening tools that have been developed, the Functional Movement Screen (FMS\(^\text{™}\)) and the Movement Competency Screen (MCS) have been investigated.\(^16\)\(^-\)\(^21\) The MCS was developed and validated for athletes and dancers.\(^16\),\(^17\),\(^21\) It has the interesting characteristic of evaluating different load levels during the performance of movements used in rehabilitation and training programs. Out of 11 movement competency assessment tools reported in the literature, the MCS was identified among the most promising to assess performance capabilities in terms of applicability and the rigor with which it was developed.\(^22\) In the original version of the MCS, Kritz described load grades as being scored using a 5-level scoring system: (1) assisted loading, (2) bodyweight loading, (3) external loading, (4) eccentric loading, and (5) plyometric loading.\(^21\) According to the currently accepted method for scoring the MCS, those five levels are regrouped into three levels as follows: (1) assisted and bodyweight loading, (2) external and eccentric loading, and (3) plyometric loading.\(^21\)

The 3-level scoring system thus collapses the five levels into three levels. For example, a movement performed with certain compensations could be rated as a 3 or a 4 on the 5-level system, while on the 3-level scoring system it would be rated as a 2. This appears to be less than optimal since the merging of load levels results in a loss of detailed information. The 5-level scoring system would allow greater precision and, as a result, would more accurately characterize movement competency. The strength of the MCS compared to other movement competency screening tools is the use of load levels. It should therefore be accounted for in detail in the scoring method.

The aim of this technical note was to investigate, in a sample of dancers, and for each MCS scoring system (1) the internal consistency between items and (2) their association with TrA activation, hip strength, and FMS\(^\text{™}\) total score. It was hypothesized that the 5-level scoring system would show better psychometric properties in terms of internal consistency and concurrent validity as assessed by association with key components of movement competency and another validated movement competency tool.

DESCRIPTION

Data for this study were gathered at one time point prior to the beginning of the 2018–2019 and 2019–2020 dance season and were derived from a prospective cohort study involving 118 dancers, varying in dance style (ballet and contemporary) and status (professional and pre-professional). Dancers were recruited following a presentation of the research project in multiple dance schools and companies. This study was approved by the institutional review board and each participant gave written informed consent. Participants had to be at least 16 years old and had to dance professionally or pre-professionally for at least 10 hours per week. They were excluded if they were pregnant because of the impact on the lumbo pelvic muscles, or if they had a musculoskeletal disorder that restricted dancing at the time of the evaluation. Participants underwent an assessment conducted by an experienced physiotherapist who has been a dancer for 17 years, a dance educator for eight years and who treats dancers in her regular practice. The assessment included the evaluation of TrA activation, hip strength, and movement competency. The evaluation was done on-site in dance schools or companies, either in a dance studio or in a physiotherapist’s office if one was available.

INDEPENDENT VARIABLES

The preferential activation ratio of the TrA was evaluated using ultrasound imaging (GE LOGIQ E, GE Healthcare, Milwaukee, Wisconsin, 13 MHz linear probe in B-mode) in a standardized position.\(^23\)\(^-\)\(^25\) Dancers were in a supine position with both knees at a 90° flexion. The probe was positioned between the axillary and mamillary lines, at mid-distance between the iliac crest and 12th rib in a transverse plane. The preferential activation ratio is calculated to take into account the activation of the internal and external obliques. This method thus considers the possible compensations of these muscles. Both sides were assessed three times and a mean value was obtained.

\[
\text{Preferential activation ratio} = \frac{\frac{TrA_{\text{AxialWld,internal}}}{\text{TrA}_{\text{AxialWld,external}}}}{\frac{TrA_{\text{AxialWld,external}}}{\text{TrA}_{\text{AxialWld,internal}}}}
\]
The strength of the hip flexors, extensors, abductors, adductors, and external and internal rotators were measured in a standardized position using a handheld dynamometer secured with straps. The exact positions used are described in a previous study. Both sides were assessed three times with a 30 second break in between each measurement. A mean value was obtained and used for analysis.

Movement competency was screened using two distinct instruments, the FMS™ and the MCS. The MCS is composed of five tasks designed to assess global movement competency: (1) squat, (2) lunge and twist, (3) bend and pull, (4) push-up and (5) single-leg squat. The lunge and twist, and the bend and pull are subdivided into the individual components of each movement. Therefore, there are seven items to be evaluated. Each item has a set of possible primary and secondary compensations. The scoring is completed by evaluating the number of compensations observed. More frequent compensations result in a lower score. Additionally, primary compensations are more detrimental to the score than secondary compensations. The tasks of the MCS can be completed with multiple load levels, according to the evaluator’s judgement. The movement can be completed slowly, rapidly, or using plyometrics. As per the accepted scoring system, the 3-level score is attributed only according to the compensations observed, with no discrimination between assisted and bodyweight loading or external and eccentric loading. The MCS was scored using both the 5-level scoring system that uses separate load levels (assisted, bodyweight, external, eccentric, and plyometric) and the 3-level scoring system in which they are grouped as described above. The FMS™ does not include different load levels. Each movement is done at a slow pace. Figure 1 shows a comparison between the movements from the MCS and the FMS™.

STATISTICAL ANALYSIS

Statistical analyses were conducted in SPSS 28.0. Cronbach’s alpha was first calculated for items scored with the 5-level system and then, for items scored with the 3-level system, to assess internal consistency. To identify the scoring system that best suited the variables, simple linear regressions were first used for the 5-level and then for the 3-level scoring system. FMS scores, TrA activation, and hip strength were used as independent variables. Each independent variable’s association with movement competency was examined, as well as the proportion of variance for the total MCS score that they each explained. A multiple regression model was built which included the variables significantly associated with the MCS score for each scoring system. Therefore, a different model was built for the 5-level and 3-level systems since the results from the simple regression analyses identified different variables as being associated with the dependent variables. Since dance hours could be a potential confounder in the analyses, each linear regression was controlled for this variable. The level of significance for all statistical analyses was set at p≤0.05. Statistical assumptions were met for each linear regression completed.

OUTCOMES

The sample was composed of 118 preprofessional and professional dancers. Table 1 presents demographic information. No adverse events occurred during the evaluations.

Table 2 presents the results of separate linear regressions between each independent variable and the MCS total score, where each item was scored using either the 5-level system or the 3-level system.

THE 5-LEVEL SCORING SYSTEM AS THE DEPENDENT VARIABLE

The internal consistency assessed with Cronbach’s alpha for the seven items of the MCS scored with the 5-level system was 0.548. It was found using simple linear regressions that TrA activation, hip extensor, abductor, adductor, and external rotator strength, as well as FMS™ total score (ß=0.455, p<0.001) were statistically significantly associated with the MCS total score as measured by the 5-level scoring system. Given multicollinearity between hip strength variables in the multiple linear regression model, only hip adductor strength was introduced in the model. This variable was chosen since it was the most significantly and strongly associated with the MCS total score. As seen in Table 3, the multivariate model accounted for 24% of the variance for the MCS scored on the 5-level system (F=13.324, p<0.001).

THE 3-LEVEL SCORING SYSTEM AS THE DEPENDENT VARIABLE

Regarding the internal consistency, Cronbach’s alpha for the seven items of the 3-level scoring system was 0.494. Simple linear regression analyses revealed significant associations with hip internal rotator strength and FMS™ total score (ß=0.250, p=0.006) with the MCS total scored on a 3-level system. Results showed that the multiple linear regression model built accounted for 13.3% of the variance for the MCS on a 3-level scoring system (F=9.959, p<0.001).

DISCUSSION

The purpose of this study was to examine the internal consistency for the items scored with each system and to explore if the association of TrA activation, hip muscle strength, and FMS score was higher with the 5-level scoring system, as opposed to the 3-level scoring system.

Although both point systems did not have a Cronbach’s alpha that exceeded the generally accepted value of 0.7 as acceptable internal consistency, the 5-level system showed a moderate internal consistency (≥0.5) and the 3-level scoring system showed a poor internal consistency (<0.5). This supports the hypothesis that the 5-level scoring system would show higher internal consistency than the 3-level scoring system.

Findings from a previous study on the correlations between the MCS total score (3-level scoring) and TrA activation, hip strength, and FMS showed significant associa-
<table>
<thead>
<tr>
<th>Movement Competency Screen (MCS)</th>
<th>Functional Movement Screen (FMS™)</th>
</tr>
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<td>In-line lunge</td>
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</tr>
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<td>Push-up</td>
<td>Trunk stability push-up</td>
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<tr>
<td>Bend &amp; Pull</td>
<td>Hurdle step</td>
</tr>
<tr>
<td><img src="image7" alt="Bend &amp; Pull" /></td>
<td><img src="image8" alt="Hurdle step" /></td>
</tr>
<tr>
<td>Single-leg squat</td>
<td>Shoulder mobility</td>
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<tr>
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<td><img src="image10" alt="Shoulder mobility" /></td>
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<tr>
<td><img src="image13" alt="Active straight leg raise" /></td>
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**Figure 1. Comparison between MCS and FMS™**
Table 1. Demographics

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<tr>
<th></th>
<th>N(%) or Mean ± SD</th>
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<tr>
<td>Sample</td>
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<tr>
<td>Age (years)</td>
<td>21.6 ± 5.2</td>
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<tr>
<td>Gender (female / male / nonbinary)</td>
<td>92 (78) / 24 (20) / 2 (2)</td>
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<tr>
<td>Style (contemporary / ballet)</td>
<td>66 (57) / 49 (43)</td>
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<td>Status (preprofessional / professional)</td>
<td>91 (78) / 25 (22)</td>
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Table 2. Simple linear regressions

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<th>MCS total score /5 as dependent variable</th>
<th>Adjusted R²</th>
<th>Standardized β</th>
<th>95% C.I.</th>
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<tr>
<td>TrA activation</td>
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<tr>
<td>Dominant side</td>
<td>0.033</td>
<td>0.203</td>
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<td>0.303</td>
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<td>Non dominant side</td>
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<td>0.200</td>
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<tr>
<th>MCS total score /3 as dependent variable</th>
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<th>Standardized β</th>
<th>95% C.I.</th>
<th>p</th>
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<tbody>
<tr>
<td>TrA activation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dominant side</td>
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<td>Hip flexor strength</td>
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<tr>
<td>Hip extensor strength</td>
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<tr>
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<td></td>
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<tr>
<td>Non dominant side</td>
<td>0.037</td>
<td>-0.214</td>
<td>[-0.097, -0.008]</td>
<td>0.020</td>
</tr>
<tr>
<td>FMS™ total score</td>
<td>0.054</td>
<td>0.250</td>
<td>[0.096, 0.575]</td>
<td>0.006</td>
</tr>
</tbody>
</table>

MCS : Movement Competency Screen; FMS™ : Functional Movement Screen; TrA : transversus abdominis

tions. However, linear regressions for the 3-level scoring system in the current study did not reveal significant association with TrA activation or hip strength, with the exception of internal rotators. In the present study, the model with the 5-level system as the dependent variable explained only 13.3% of the variance. In a previous model using the 3-level system, similar independent variables could explain only 10.8% of the variance. In the current study, it was found that 24% of the variance for the total MCS score using the 5-level system could be explained by the independent variables selected. These results are of particular interest because they show that the variance of the 5-level scoring system is explained in a greater proportion by components that have been identified as key to movement competency. This supports the assumption that the 5-level scoring system shows higher concurrent validity.

This study is not the first to reconsider the MCS scoring system instead of using the common 3-level scoring for only the
Table 3. Multiple linear regression

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Adjusted R²</th>
<th>Standardized β</th>
<th>95% C.I.</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>TrA activation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant side</td>
<td>0.240</td>
<td>0.115</td>
<td>[-0.595, 3.482]</td>
<td>0.163</td>
</tr>
<tr>
<td>Hip adductor strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non dominant side</td>
<td>0.195</td>
<td>[0.009, 0.109]</td>
<td></td>
<td>0.021</td>
</tr>
<tr>
<td>FMSᵀᴹ total score</td>
<td>0.389</td>
<td></td>
<td>[0.582, 1.446]</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

MCS total score /5 as dependent variable

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Adjusted R²</th>
<th>Standardized β</th>
<th>95% C.I.</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip internal rotator strength</td>
<td>0.133</td>
<td>-0.303</td>
<td>[-0.118, -0.031]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Non dominant side</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMSᵀᴹ total score</td>
<td>0.332</td>
<td></td>
<td>[0.208, 0.684]</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

MCS total score /3 as dependent variable

CONCLUSION

The items scored with the 5-level system showed higher internal consistency of the test scores than with the 3-level system. Simple and multiple linear regressions used in the present technical note indicate that a 5-level system is more representative of the essential components of movement competency than the commonly used 3-level system because of its higher and more significant association with TrA activation, hip strength, and FMSᵀᴹ score. For these reasons, health professionals and researchers should consider using the 5-level scoring system of the MCS in future clinical settings and research.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

FUNDING

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Original Research

An Updated Model Does Not Reveal Sex Differences in Patellofemoral Joint Stress during Running

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Keywords: knee, kinetics, patellofemoral pain, biomechanics

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Background
Structure-specific loading may have implications in understanding the mechanisms of running related injury. As females demonstrate a prevalence of patellofemoral pain twice that of males, this may indicate differences in patellofemoral loads between males and females. Previous works investigating differences in patellofemoral joint stress have shown conflicting results, but the models employed have not used estimates of muscle forces or sex specific contact areas.

Hypothesis/Purpose
The aim of this study was to examine sex differences in patellofemoral joint stress using an updated model to include estimates of quadriceps muscle force and sex-specific patellofemoral contact area.

Study Design
Descriptive Laboratory Study

Methods
Forty-five healthy recreational runners ran at a controlled speed down a 20-meter runway. Kinetic and kinematic data were utilized to estimate muscle forces using static optimization. Quadriceps muscle force was utilized with sex-specific patellofemoral joint contact area in a two-dimensional patellofemoral joint model to estimate patellofemoral joint stress. Multivariate tests were utilized to detect sex differences in patellofemoral loading and hip and knee kinematics.

Results
No differences were found between sexes in measures of patellofemoral loading or quadriceps force. Females displayed a reduced knee extension moment and greater hip adduction and internal rotation than males.

Conclusion
The inclusion of static optimization to estimate quadriceps muscle force and sex-specific contact area of the patellofemoral joint did not reveal sex differences in patellofemoral joint stress, but differences in non-sagittal plane hip motion were detected. Therefore, two-dimensional patellofemoral models may not fully characterize differences in patellofemoral joint stress between males and females. Three-dimensional
patellofemoral models may be necessary to determine if sex differences in patellofemoral joint stress exist.

**Level of Evidence**

3b

**INTRODUCTION**

Structure-specific loading has become of interest, especially pertaining to overuse running injuries. This premise seeks to understand how elements of running biomechanics, such as different kinematic and kinetic features of running, may lead to stresses on tissues that predispose those structures to injury. This has implications to understanding common running injuries such as patellofemoral pain (PFJP). Patellofemoral pain has been reported as the most common running related injury accounting for 16.5% of all injuries presenting to a running clinic. More recently, a systematic review and meta-analysis has estimated an incidence rate of 1080.5/1000 person-years in amateur runners. As increased patellofemoral joint stress (PFJS), patellofemoral bone stress, and cartilage strain have been implicated in PFJP and certain running kinematics and kinetics may increase structure-specific loading (i.e. PFJS), understanding differences in structure-specific loading between sexes may be relevant to the development of this common injury.

As PFJP is two times more prevalent in females, it has been proposed that females may demonstrate increased PFJS leading to greater structure-specific load. Although the theoretical link is clear, studies investigating sex differences in PFJS have shown mixed findings. Almonroeder & Benson reported males had greater PFJS and patellofemoral joint reaction force (PFJRF) during running, while there were no differences between sexes in knee extension moments or knee flexion. Sinclair & Selfe reported females had greater patellofemoral contact force, PFJS, and peak knee extension moment compared to males, while Willson et al. did not demonstrate sex differences in PFJS, PFJRF, or knee extensor moment.

To understand these discrepancies, important differences should be noted in the musculoskeletal modeling approaches employed. First, two studies utilized estimates of PFJS based on inverse dynamics methods that calculate joint stress directly using the knee extension moment. This may not account for any potential muscle co-contraction. Therefore, inverse dynamics approaches alone may lead to underestimation of PFJS.

Willson et al. adjusted their model to account for the force of the knee flexors but how this method compares to other approaches estimating quadriceps force is unknown. Static optimization based methods used to estimate muscle forces yield different values of PFJS compared with inverse dynamic approaches. Therefore, estimates of PFJS from musculoskeletal models utilizing muscle forces may provide a more robust estimate of quadriceps loading for estimates of PFJS.

Methods used to estimate patellofemoral joint contact area (PFJCA) is another factor that may explain the different findings associated with PFJS based on sex. Almonroeder & Benson used in vivo measurements in females obtained via MRI to estimate PFJCA despite testing a mixed sex sample. Willson et al. used similar data that were sex-specific while Sinclair & Selfe used data from cadaveric, non-sex specific samples. As PFJCA differences have been reported between sexes, it seems imperative to utilize sex-specific contact areas in attempts to elucidate differences in PFJS.

A combination of utilizing quadriceps muscle force estimates from static optimization and sex-specific PFJCA may help to clarify inconsistencies reported in previous studies examining sex differences in PFJS, lead to further understanding of tissue stresses imposed on the patellofemoral joint during running, and help guide future research.

The purpose of this study was to examine sex differences in patellofemoral joint stress using an updated model to include estimates of quadriceps muscle force and sex-specific patellofemoral contact area. It was hypothesized that females would demonstrate increased PFJS when quadriceps muscle force and sex-specific contact area were considered.

**METHODS**

**PARTICIPANTS**

Using the peak patellofemoral joint stress differences from Willson et al., an alpha = 0.05, a correlation between scores of 0.5 to determine a power of 0.8, a sample size of 18 subjects was calculated. Twenty-four healthy females and 21 males participated (Table 1). Inclusion criteria: self-reported running routine of greater than 16 km/week, rearfoot strike pattern (first ground contact made with the heel) while running, score of ≥5 on the Tegner scale, and no reported injuries limiting regular running participation within the prior 12 months. Exclusion criteria: pregnancy, reported cardiovascular pathology, and surgery to either lower extremity within the prior 12 months. All subjects provided informed consent approved by the Institutional Review Board at the university.

### Table 1. Demographic factors reported as means (SD).

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>21.8 (1.5)</td>
<td>21.1 (2.2)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>167.6 (6.4)</td>
<td>179.1 (8.2)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>62.0 (8.1)</td>
<td>74.6 (10.3)</td>
</tr>
<tr>
<td>Tegner Scale</td>
<td>6 (5-7)</td>
<td>6 (5-9)</td>
</tr>
</tbody>
</table>

Tegner scale is reported as the median (range).
PROTOCOL

A static trial was completed to calibrate the musculoskeletal model. Then after a minimum of three practice running trials, participants ran down a 20-m runway using their typical rearfoot running pattern. Pattern was verified using the foot strike index where the center of pressure at ground contact was located in the rear third.14

Speed was restricted to a range of 3.52-3.89 m/s using photocells interfaced with a digital clock. Range was chosen to ensure comparable running speeds were present between groups. Running pattern was observed and no targeting of the force plate was allowed. A minimum of five successful right leg trials were completed.

INSTRUMENTATION

Prior to running, participants were prepped for motion analysis. Forty-seven retroreflective markers were applied to each participant’s skin, tight fitted clothing, or footwear as previously described.15 Markers were left in place during data collection and data were captured at 180 Hz via 15 Motion Analysis cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) surrounding the runway. Ground reaction forces were collected with a force platform (Model 4080, Bertec Corporation, Columbus, OH, USA) flush with the runway. Analog data were sampled at 1800 Hz. Both analog data from force platforms and kinematic data were processed through a low-pass Butterworth filter at 12 Hz.

DATA PROCESSING

The Human Body Model (HBM, Motek Medical, Amsterdam, Netherlands) was used to calculate muscle forces using a 44 degree of freedom (DOF) musculoskeletal model with 16 rigid segments.16 The hip joint was treated as a ball-in-socket joint based on Bell et al.17 The knee joint was modeled as a single DOF hinge where any tibio-femoral translations and non-sagittal rotations were constrained as a function of knee flexion. Limb segments and inertial characteristics were sex-specific.18 From estimates of hip joint center from the standing neutral trial and estimates of the of sacroiliac joint center,19 the HBM creates pelvic geometry for each participant.

Eighty-six muscles were modeled in the lower extremities where the muscle insertion points and wrapping points were from Delp.20 A kinematic solver within HBM used global optimization to determine skeletal model kinematics.21,22 Joint moments were then obtained from equations of motion and estimated by minimizing a static cost function where the sum of squared muscle activations is related to maximum muscle strengths at each time step.20 A recurrent neural network was used to solve the static optimization problem.23

The muscle forces from the HBM were then used to quantify the total quadriceps force (QF) by summing the muscle forces of the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius. PFJS is calculated by dividing PFJRF by the PFJCA. To determine the PFJRF, a conversion factor (k) was estimated from Brechter & Powers24:

\[
k(x) = \frac{4.62e^{-0.1} + 1.47e^{-0.3}x - 3.84e^{-0.5}x^2}{1 - 1.62e^{-0.2}x + 1.55e^{-0.4}x^2 - 6.98e^{-0.7}x^3}
\]

where x is the knee joint angle in the sagittal plane. This represented the portion of the quadriceps force acting directly on the patellofemoral joint. Both knee angle and the orientation of the quadriceps muscle affect force imposed on the patellofemoral joint. Therefore,

PFJRF(x) = k(x) × QF(x).

Sex-specific PFJCA was calculated as a function of knee angle using the data reported from Besier et al.13 to formulate predictive equations:

Females: PFJCA(x) = 191.336 + 5.479x

Males: PFJCA(x) = 311.3227 + 5.732x

PFJS was then calculated as follows:

PFJS(x) = PFJRF(x)/PFJCA(x)

DATA ANALYSIS

A multivariate analysis of variance (MANOVA) was used to examine any sex differences in peak PFJS, PFJRF, QF, knee extensor moment, peak knee flexion, peak hip adduction, and internal rotation during the stance phase of running (α=0.05). Follow up univariate tests were performed to assess sex differences in these same kinetic and kinematic data. A Bonferroni correction was employed. Statistical calculations were performed in SPSS 24.0 (IBM, Armonk, NY, USA). Effect sizes were calculated using partial eta squared (η²) where a small effect size was considered as η²<0.06, a medium effect size 0.06≤η²<0.14, and a large effect size η²≥0.14.

RESULTS

Multivariate differences were shown on sex (Wilk’s lambda = 0.456; p =0.000). From follow up univariate tests, there were no differences between the sexes in peak PFJS (Figure 1), PFJRF, QF, or knee flexion angle shown during running (Table 2). Females showed 11.7% less knee extensor moment compared to males (p = 0.049). Effect sizes for peak PFJS, PFJRF, QF and knee flexion angle were small while a medium effect size was present for knee extensor moment (Table 2).

Follow up univariate tests showed hip adduction (Figure 2A) and internal rotation (Figure 2B) were different between sexes. Females demonstrated 111% greater peak value for hip internal rotation (absolute difference: 3.62°). Females also demonstrated 48.5% greater hip adduction (absolute difference: 4.80°) than males. A large effect size was present for hip adduction and medium effect size was present for hip internal rotation (Table 2).

DISCUSSION

The aim of this study was to examine sex-related differences in patellofemoral joint loads. Even with static optimization and sex-specific contact areas, no differences in PFJS, PFJRF, or QF were shown between sexes during running. However, females demonstrated less knee exten-
sion moment and greater transverse and frontal plane hip motion than males. The presence of a sex difference in knee extension moment and lack of a sex difference between QF may indicate that the use of muscle force estimates could be important in describing sex differences in PFJS. Further, as hip motion may affect loads at the patellofemoral joint,\textsuperscript{25,26} more comprehensive models of the patellofemoral joint may be needed to account for these motions. Since muscle force estimates to derive PFJRF and sex-specific contact areas did not detect sex differences in PFJS, a consideration of frontal and transverse plane contributions to PFICA in conjunction with muscle force estimates may be necessary to detect such differences. Further characterization of PFJS with the use of 3D patellofemoral joint models may be a necessary step in understanding structure-specific load based on sex.

Results were contrary to what was hypothesized. This study and previous work on sex differences in patellofemoral joint loading have had inconsistent findings.\textsuperscript{9–11} Several aspects of approaches used within previous models could have contributed to these inconsistencies that attempts were made to account for in the current investigation. This was an attempt to build on previous efforts by improving on the available 2D models to see if inclusion of muscle forces and a sex-specific PFJ model could support the hypothesis that females demonstrate greater PFJS. Yet, even with these additions, no differences in peak PFJS were detected. Based on a qualitative assessment of the average ensemble PFJS time series data, it appears that males had a later peak in PFJS during stance (65\% of stance vs. 57\% of stance). However, in both males and females, peak QF seemed to occur at nearly the same time as peak PFJS during stance (65\% and 60\%, respectively) whereas knee flexion occurred only slightly later in stance for males (69\% of stance) but a larger difference in the timing of peaks was seen in females (peak knee flexion occurred at 67\% of stance in females). This may depict that males are displaying a peak PFJS and QF closer to the time of peak knee flexion where PFICA is increased as the knee is more flexed. Therefore, this might indicate that males may be

\begin{table}[h]
\centering
\caption{Peak values of selected variables.}
\begin{tabular}{|l|c|c|c|c|}
\hline
 & Females & Males & \textit{p} value & Effect Size ($\eta^2$) \\
\hline
PFJS (MPa) & 9.20 (1.65) & 9.32 (2.22) & 0.829 & 0.001 \\
PFJRF (BW) & 6.89 (1.22) & 7.24 (1.52) & 0.391 & 0.017 \\
QF (BW) & 7.82 (1.17) & 8.28 (1.50) & 0.249 & 0.031 \\
Knee extensor moment (N\*m/kg) & 0.869 (0.136) & 0.984 (0.239) & 0.049 & 0.087 \\
Knee flexion (degrees) & 48.4 (5.00) & 46.6 (5.20) & 0.244 & 0.031 \\
Hip adduction (degrees) & 14.7 (4.07) & 9.90 (4.20) & 0.000 & 0.259 \\
Hip internal rotation (degrees) & 6.89 (5.71) & 3.26 (5.28) & 0.034 & 0.101 \\
\hline
\end{tabular}
\footnotesize{Values are presented as group averages with standard deviations. Bold type indicates statistically significant differences.}
\end{table}
Figure 2. Ensemble averages of hip adduction (A) and hip internal rotation (B) over the stance phase of running.

demonstrating peak QF during stance when the knee is in a more desirable position to distribute these patellofemoral contact forces across the patellofemoral joint. However, this hypothesis needs further examination. In addition, the lack of differences in peak patellofemoral forces shown here may indicate that 2D models may be insufficient to fully characterize PFJS based on sex.

Estimates of PFJS from static optimization are higher as inverse dynamics does not account for co-contraction of muscles crossing the same joint. In the present study, peak knee extension moment during stance was similar to previous studies. In previous work, Almonroeder et al. reported females had 12.9% less knee extension moment than males, whereas Sinclair & Selfe reported females demonstrating 14.1% greater knee extension moment than males, and Willson et al. reported no differences between sexes. Differences may be related to how individuals co-contract their knee flexors and extensors to control knee motion during running. These results from the current study showed differences between sexes in knee extension moment, but not in QF. This may indicate differences between sexes in the muscle force production of the knee flexors during stance may affect the net knee moment. Consideration of muscle forces from static optimization may be an important in portraying PFJS.

As PFJS is the quotient of PFJRF and PFJCA, differences in either of these can also explain study differences. Despite sex-specific estimates of PFJCA, no differences in PFJS between males and females was identified. However, consistent with previous studies, peak hip adduction and internal rotation during the stance phase of running were greater in females. Although statistical differences were detected in non-sagittal plane hip motions, the meaningfulness of these small differences is uncertain. However, the reported differences appear consistent with previously reported literature where females display more non-sagittal hip motion during running than males.

Hip positioning has been demonstrated as impacting PFJCA and, thus, measures of PFJS in individuals with and without PFP. This occurs as frontal and transverse
plane rotations at the hip can position the femur and the patella in a way that the location and contact area is either increased or decreased. Liao & Powers\textsuperscript{26} reported that the location and magnitude of peak patella cartilage stress did not differ between runners with and without PFJS. These authors did find, however, that tibiofemoral rotations in both the transverse and frontal planes explained 45% and 26% of the variance in patellar cartilage stress, respectively. Further, when investigating the isolated role of tibial and femoral rotations on patellar cartilage stress, it has been reported that increased femoral internal rotation of 4°, 6°, 8°, and 10° yielded increases in patellar cartilage stress ranging from 41–77%.\textsuperscript{25} Similarly, increases in 10° of femur adduction produced increases in patellar cartilage stress of 43%.\textsuperscript{25}

Therefore, even small changes in femoral rotation may have a notable impact on PFJS. Since there was nearly a 4–5° difference shown between males and females in both femoral internal rotation and adduction, it is likely that these differences in hip kinematics here would have influenced the magnitude of PFJS in participants. As the model used in this study did not utilize frontal or transverse plane knee motion to determine PFJS, sex differences in patellofemoral joint loads may have gone undetected. Therefore, the lack of observed differences between sexes even with quadriceps muscle force estimates supports the notion that if sex differences in PFJS exist it may be related to differences in frontal and transverse plane kinematics at the patellofemoral joint. If contributions from the frontal and transverse planes can be characterized and quantified, this may assist clinicians in assessing when increased hip motion may be a contributing factor to a patient’s presentation. Further research characterizing the effects of femoral orientation on patellofemoral joint loads by sex in running appears warranted.

Despite the attempts to build on the work of previous authors, several limitations to the approach used should be noted. First, the patellofemoral model was limited to two-dimensional and was incapable of capturing frontal and transverse plane motions. This was largely due to the limitations of the musculoskeletal model Constraining the knee to one degree of freedom. However, this model attempted to build upon previous work using 2D models by including muscle force estimates and sex-specific 2D estimates of PFJCA in the model. Next, all musculoskeletal models utilize numerous anatomical assumptions to yield estimates of muscle force. As these do not necessarily reflect the anatomy of the included participants, there is an amount of error inherent to this approach. Therefore, the degree to which these estimates reflect the actual physiological loads is still questionable and therefore may not fully reflect the true patellofemoral joint loading present. Thirdly, running speed was controlled for all participants to assist with comparisons between groups. As joint kinematics and muscle forces change with running speed,\textsuperscript{31,32} the patellofemoral joint loading estimated here may not reflect the loads regularly imposed on the individual participants during their typical training runs. Additionally, only rearfoot strike runners were examined as forefoot striking appears to alter patellofemoral joint stress.\textsuperscript{15,33} To what extent sex differences in PFJS is present in those who employ a non-rearfoot strike pattern is unknown. Because only healthy runners were investigated, these findings may not be applicable to injured runners. Finally, differences in running experience were not accounted for. As aspects of running mechanics can differ with greater experience,\textsuperscript{34} how these results may differ in novice versus experienced runners is uncertain.

CONCLUSION

The results of the current study indicate that there was no difference between sexes in PFJS during the stance phase of running despite the use of quadriceps muscle force and sex-specific contact area estimates in a 2D patellofemoral joint model. Differences were noted between sexes in knee extension moment yet not in quadriceps force. This indicates that the methods employed to estimate PFJRF should be considered when comparing modeling approaches utilized. Further, peak hip adduction and internal rotation angles during running were greater in females compared to males. Since quadriceps muscle force estimates did not reveal sex differences in PFJS, it is plausible that, if these differences exist, they may be related to frontal and transverse plane kinematics. Utilization of 3D models that incorporate transverse and frontal plane kinematics of the patellofemoral joint in conjunction with estimates of quadriceps muscle force may be necessary to characterize potential differences in PFJS between sexes and may help clinicians identify risk factors for PFP.

DEclarations OF INTERest

The authors have no financial conflicts of interest to declare.

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Original Research

Deficits in Dynamic Balance and Hop Performance Following ACL Reconstruction Are Not Dependent on Meniscal Injury History

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Keywords: anterior cruciate ligament reconstruction, knee, rehabilitation, return to sport, meniscus

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Background
Athletes often exhibit persistent deficits in dynamic balance and hop performance in their involved limb following ACL reconstruction. However, it is unclear how meniscal injury history affects inter-limb asymmetry.

Purpose
The purpose of this study was to compare inter-limb asymmetry in dynamic balance and hop performance in athletes with and without a history of concomitant meniscal injury.

Study Design
Cross-sectional study

Methods
Dynamic balance and hop test data were analyzed for 34 adolescent athletes who had undergone ACL reconstruction; 19 athletes had sustained an isolated ACL tear, while 15 had sustained an ACL tear along with a meniscus injury. Athletes who had sustained a meniscus injury were sub-divided into those who underwent a meniscal repair (n = 9) versus a partial meniscectomy (n = 6). Dynamic balance was assessed using the Y-Balance Test, while hop performance was assessed using the single and triple hop tests. Data were recorded at the time of return-to-sport testing (5-11 months post-surgery). For each variable, mixed-model analysis of variance, with a between-subjects factor of group (isolated ACL tear, meniscal repair, partial meniscectomy) and a within-subjects factor of limb (involved, uninvolved), was conducted.

Results
The groups exhibited similar degrees of inter-limb asymmetry in dynamic balance and hop test performance, as there was not a group-by-limb interaction effect for the Y-Balance Test distances (p ≥ 0.43) or hop test distances (p ≥ 0.96). However, there was a main effect of limb for the anterior and posteromedial Y-Balance Test distances and the single and triple hop test distances (p ≤ 0.004). For each variable, performance was worse for the involved limb, compared to the uninvolved limb.

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INTRODUCTION

Anterior cruciate ligament (ACL) tears are common among high school age athletes who participate in sports that involve frequent single-leg landing, cutting, and pivoting.\(^1,2\) Athletes who have sustained an ACL tear typically undergo ACL reconstruction and then complete extensive post-operative rehabilitation.\(^3\) Approximately one in five of these athletes will go on to sustain a second ACL injury shortly after returning to sport.\(^4\) This alarmingly high injury rate highlights the urgent need to examine factors that may influence an athlete’s ability to safely return to sport following ACL reconstruction.

Athletes who have undergone ACL reconstruction often demonstrate deficits in postural stability and dynamic balance for their involved limb (vs. their uninvolved limb), even after completing post-operative rehabilitation.\(^5–7\) This is concerning since deficits in postural stability and dynamic balance are associated with an increased risk for ACL injury/re-injury.\(^8,9\) Athletes who have undergone ACL reconstruction also tend to exhibit persistent (12+ months post-surgery) deficits in single leg hop performance for their involved limb,\(^10–12\) which is likely due, at least in part, to limitations in lower extremity strength and power generation.\(^11\) These types of persistent neuromuscular deficits may contribute to re-injury and/or limit an athlete’s ability to return to their prior level of sport performance.

Factors such as quadriceps weakness\(^13,14\) and kinesiophobia\(^15,16\) have been studied extensively and appear to contribute to the persistent deficits in dynamic balance and hop performance commonly exhibited by athletes following ACL reconstruction. However, one potential factor that has not been thoroughly examined is an athlete’s meniscal injury history. At this time, only one previously published study has compared dynamic balance for athletes with and without a history of concomitant meniscal injury\(^15\) and no studies have examined how meniscal injury status affects inter-limb symmetry in hop performance. It is important to further examine the influence of meniscal injury history since more than half of all ACL tears are accompanied by a meniscus tear,\(^17–19\) with 56% of tears involving the lateral meniscus and 44% of tears involving the medial meniscus.\(^17\) It is also important to examine whether neuromuscular performance is affected by how an athlete’s meniscal tear was managed. While surgeons typically attempt to repair the meniscus if possible, in some cases they must debride the injured part of the meniscus (partial meniscectomy). This could potentially negatively impact knee control, since the menisci serve as a source of mechanical stability for the knee.\(^20–22\)

Therefore, the purpose of this study was to compare inter-limb asymmetry in dynamic balance and hop performance for athletes with and without a history of concomitant meniscal injury. It was hypothesized that the degree of interlimb asymmetry in dynamic balance and hop performance would be similar for athletes with isolated ACL tears, compared to athletes with concomitant meniscal injuries, regardless of whether they had undergone meniscal repair or partial meniscectomy.

MATERIALS AND METHODS

PARTICIPANTS

Clinical outcomes for 34 adolescent athletes were analyzed as part of this cross-sectional study; 19 (9 males, 10 females) of these athletes had sustained an isolated ACL tear, while 15 (8 males, 7 females) had sustained an ACL tear along with a partial meniscus tear. All athletes were competing at the high school level at the time of injury and were between 14-19 years of age at the time of testing. This age range aligns with the World Health Organization’s definition of adolescence.\(^23\) To be included in this study, athletes needed to have undergone successful primary unilateral ACL reconstruction (either bone-patellar tendon-bone autograft or hamstring tendon autograft), completed conventional post-operative rehabilitation, participated in facility-standard return to sport testing (which included testing of dynamic balance and hop performance), and expressed an intention to return to competitive sports. Data were excluded for athletes with a history of major injury or surgery for their uninvolved limb, a history of major injury or surgery for their involved limb (aside from their ACL injury/reconstruction), or a concomitant ligament injury (e.g. medial collateral ligament tear). ACL reconstruction surgeries were performed by one of a group of five orthopedic surgeons. All athletes had completed post-operative rehabilitation (see Rehabilitation Protocol sub-section for details) with the same physical therapist who is a board-certified sports clinical specialist through the American Board of Physical Therapy Specialists. The athletes had resumed high-level dynamic activities, such as landing and jumping, but had not been cleared to return to sport at the time of testing. At the time of testing, none of the athletes had notable limitations in knee range of motion (beyond what could be attributed to measurement error) or visible signs of effusion for their involved knee. The athletes who had sustained a meniscal injury had either undergone a meniscal repair (n = 9) or a partial meniscectomy (n = 6). Study data were obtained through retrospective chart review. This

Conclusion

It appears that deficits in dynamic balance and hop performance among adolescent athletes who have undergone ACL reconstruction are not dependent on meniscal injury/surgery history.

Level of Evidence

3
study protocol was approved by the Institutional Review Board at Lutheran Hospital (Fort Wayne, IN, USA).

REHABILITATION PROTOCOL

The athletes’ rehabilitation generally progressed through four phases (a copy of the protocol is included as supplementary material). Phase 1 focused on controlling swelling/effusion, increasing knee motion, maintaining patellar mobility, facilitating quadriceps activation and strength, and initiating and progressing weight-bearing. Phase 2 focused on regaining full knee range of motion, improving quadriceps and hamstring strength, normalizing walking gait, promoting knee control during functional tasks, general lower body strengthening, and aerobic conditioning. Phase 3 focused on more advanced strengthening and conditioning, initiation and progression of running, jumping, and cutting, and sport-related training. Phase 4 focused on more advanced strengthening and training to promote sport-specific skills (e.g. sprinting, agility drills). Rehabilitation followed this general protocol for all athletes; however, athletes progressed through the stages at different rates, depending on a variety of factors (e.g. surgical factors, rate of recovery). Return-to-sport testing was conducted once athletes exhibited full knee motion (based on goniometric measurements), minimal pain/effusion, symmetrical strength for their involved limb (within 90% of the uninvolved limb, based on standardized testing with a handheld dynamometer), and no major movement faults (e.g. quadriceps avoidance, excessive knee valgus) during dynamic activities such as landing, jumping, and cutting (based on visual observation by the therapist). At the time of testing all athletes had successfully “completed” rehabilitation from the standpoint of they had met the criteria for formal return-to-sport testing.

STUDY PROCEDURES

The data analyzed as part of this study were recorded at the time of the athletes’ return-to-sport testing session (within a range of 5-11 months after surgery). To promote consistency, testing was standardized and administered by the same physical therapist who has extensive experience in administering the tests used in this study. Subjects wore their own athletic shoes during testing.15

HOP TESTING

All athletes completed the single hop test and triple hop test, which are both common performance-based outcome measures used to assess knee-related function and lower extremity strength/power following ACL reconstruction.24,25 For each hop test, the athlete was given a demonstration, performed a practice trial with each limb, and then completed two successful trials per limb, with the uninvolved limb tested first.24,25 Successful trials were defined as trials where the athlete was able to maintain single-limb stance for at least two seconds upon the final landing.25 Unsuccessful trials, such as when an athlete was unable to maintain single-limb stance for at least two seconds, were repeated (up to two repeat trials per limb). The average of the two successful trials was recorded as the outcome of interest. No restrictions were placed on arm movement during hop testing.25 Hop testing was performed in a fieldhouse with artificial field turf.

For the single hop test, the athletes initiated the test in single-limb stance (test limb) with their toes behind a marked line. They then hopped forward for maximal distance, landing on their test limb. Hop distances were measured in centimeters using a tape measure affixed to the turf. Measurements were taken at the point of the heel of the athlete’s shoe for the test limb. The triple hop test was completed in the same manner, except the athlete completed three consecutive maximal hops with their test limb.

Performance on both the single hop test and triple hop test have been shown to demonstrate excellent test-retest reliability, are sensitive to changes for the involved limb over the course of rehabilitation, and correlate with perceived lower extremity function in athletes with a history of ACL reconstruction.25,26

DYNAMIC BALANCE TESTING

Similar to the hop tests, the athletes completed the Lower Quarter Y Balance Test (also referred to as the modified Star Excursion Balance Test) with both their involved and uninjured limbs. A Y-Balance Test kit was used to record test performance (Functional Movement System; Danville, VA, USA). The Y-Balance Test is a commonly used clinical test to assess single leg dynamic balance. As part of the test, athletes must maintain their balance on a single limb (test limb) while reaching as far as possible in the anterior, posteromedial, and posterolateral directions with their contralateral limb, while a sliding indicator is used to mark their reach distance (Figure 1). Athletes completed three trials per limb in each direction. An examiner recorded the single farthest distance reached (centimeters) for each direction. As recommended, the athletes were given a demonstration of the test and completed practice trials in each direction prior to formal testing.27 Athletes completed three trials with their right limb and then three trials with their left limb in the anterior direction.27 The same testing procedures were then completed in the posteromedial and posterolateral directions. As recommended,28 athletes where required to maintain their hands on their hips when completing the Y-Balance Test in order to limit their ability to use their upper extremities to assist in maintaining stability.29,30 This allows for a more direct assessment of lower body neuromuscular control, since it limits an athlete’s ability to stabilize themselves with their upper extremities.28 Trials were considered invalid if the athlete failed to maintain single-leg stance throughout the trial, failed to maintain foot contact with the indicator when reaching, used the indicator for support, or removed their hands from their hips during a trial.13,27

The Y-Balance Test has been shown to demonstrate excellent intrarater and interrater reliability.31 In addition, relatively poor Y-Balance Test performance has been found to be associated with an increased risk of sport-related non-contact lower extremity injury, including ACL tears.9,31
Figure 1. Example of an individual completing the Y-Balance Test in the anterior (left panel), posteromedial (middle panel), and posterolateral (right panel) directions. In this case, the dynamic balance of the individual’s left limb is being assessed.

STATISTICAL ANALYSIS

The dependent variables of interest were the reach distances for the Y-Balance Test (anterior, posteromedial, and posterolateral directions) and the hop distances for the single hop test and triple hop test. For each variable, a two-way, mixed-model analysis of variance with a between-subjects factor of group (isolated ACL tear, meniscal repair, partial meniscectomy) and a within-subjects factor of limb (involved, uninvolved) was conducted. An alpha level of 0.05 was used for each test of statistical significance. In addition, 95% confidence intervals (CI95%) were generated to supplement the results of the null hypothesis significance tests.

A limb symmetry index (LSI) was also generated for each variable by dividing the distance for the involved limb by the distance for the uninvolved limb and then multiplying by 100 to express as a percentage.6,24,25 An LSI equal to 100% reflects perfect inter-limb symmetry, an LSI less than 100% reflects poorer performance for the involved limb, and an LSI greater than 100% reflects poorer performance for the uninvolved limb. SPSS software was used for statistical analysis (Version 28; IBM Corp., Armonk, New York, USA).

RESULTS

Table 1 describes the characteristics of the athletes whose data were analyzed as part of this study.

There was not a group-by-limb interaction effect for the anterior [F (2, 31) = 0.26; p = 0.77], posteromedial [F (2, 31) = 0.86; p = 0.43], or posterolateral [F (2, 31) = 0.41; p = 0.67] Y-Balance Test reach distances, or the single hop test [F (2, 31) = 0.04; p = 0.96] or triple hop test distances [F (2, 31) = 0.03; p = 0.97], which indicates that the groups exhibited similar degrees of inter-limb asymmetry in dynamic balance and hop test performance.

There was a main effect of limb for the anterior [F (1, 31) = 16.52; p < 0.001] and posteromedial [F (1, 31) = 9.76; p = 0.004] Y-Balance Test reach distances; however, there was not a main effect of limb for the posterolateral direction [F (1, 31) = 1.56; p = 0.22] (Figure 2). On average, Y-Balance Test reach distances were 2.7 cm less in the anterior direction [CI95% = (-3.8 cm, -1.6 cm)] and 3.3 cm less in the posterolateral direction [CI95% = (-5.1 cm, -1.5 cm)] for the involved limb, compared to the uninvolved limb.

There was also a main effect of limb for the single hop test [F (1, 31) = 15.55; p < 0.001] and triple hop test [F (1, 31) = 20.92; p < 0.001] distances (Figure 2). Single hop test distances were 19.2 cm less for the involved limb [CI95% = (-27.5 cm, -10.8 cm)] and triple hop test distances were 57.5 cm less for the involved limb [CI95% = (-80.1 cm, -34.9 cm)], compared to the uninvolved limb.

There was not a main effect of group for any of the variables of interest (p > 0.12).

DISCUSSION

The purpose of this study was to compare inter-limb asymmetry in dynamic balance and hop performance for athletes with and without a history of concomitant meniscal injury. As hypothesized, the degree of interlimb asymmetry in dynamic balance and hop performance was similar among athletes with isolated ACL tears and athletes with concomitant meniscal injuries who had undergone meniscal repair or partial meniscectomy. Each group of athletes (isolated ACL tear, meniscal repair, partial meniscectomy) exhibited deficits in dynamic balance and hop performance for their involved limb, vs. their uninvolved limb (main effect of limb). In general, it appears that deficits in dynamic balance and hop performance following ACL reconstruction are not dependent on meniscal injury history.

A previous study by Clagg et al.13 also compared Y-Balance Test performance at the time of return to sport (average of 6.7 months after ACL reconstruction) for athletes with isolated ACL tears vs. those with concomitant meniscal injuries. Although the investigators did not examine inter-limb symmetry, their results were generally consistent...
Table 1. Characteristics of the athletes in the isolated ACL tear, meniscal repair, and partial meniscectomy groups.

<table>
<thead>
<tr>
<th></th>
<th>Isolated ACL tear</th>
<th>Meniscal Repair</th>
<th>Partial Meniscectomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of athletes</td>
<td>19</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Injured limb (right/left)</td>
<td>8/11</td>
<td>4/5</td>
<td>4/2</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>9/10</td>
<td>4/5</td>
<td>4/2</td>
</tr>
<tr>
<td>Age (years)</td>
<td>16.7 ± 1.5</td>
<td>16.3 ± 1.0</td>
<td>16.5 ± 0.6</td>
</tr>
<tr>
<td>Days since surgery</td>
<td>196 ± 41 (151-315)</td>
<td>233 ± 58 (166-327)</td>
<td>164 ± 8 (156-174)</td>
</tr>
</tbody>
</table>

Mean ± standard deviation for age and days since surgery
Minimum and maximum number of days since surgery is also reported (minimum–maximum)

Figure 2. Mean (± 95% confidence interval) limb symmetry index values based on the Y-Balance Test distances (anterior, posteromedial, and posterolateral directions) for the athletes in the isolated ACL tear (black), meniscal repair (grey), and partial meniscectomy (white) groups. Limb symmetry index values less than 100% reflect worse performance for the involved limb, compared to the uninvolved limb.

Figure 3. Mean (± 95% confidence interval) limb symmetry index values based on the hop test distances for the athletes in the isolated ACL tear (black), meniscal repair (grey), and partial meniscectomy (white) groups. Limb symmetry index values less than 100% reflect worse performance for the involved limb, compared to the uninvolved limb.

with those of the current study, as they found no significant differences in involved-limb anterior, posteromedial, or posterolateral Y-Balance Test reach distances for athletes with isolated ACL tears vs. those with concomitant meniscal injuries. Considering the results reported by Clagg et al.,15 as well as those of the current study, it does not appear that deficits in dynamic balance differ for athletes with and without a history of concomitant meniscal injury. While Clagg et al.13 reported the average single hop test and triple hop test distances for their entire cohort of athletes, they did not compare hop performance based on meniscal injury history. They also did not differentiate between athletes who had undergone meniscal repairs vs. those who had undergone partial meniscectomies, as they grouped these athletes together in their analysis.

The results of this study suggest that athletes who have undergone ACL reconstruction exhibit deficits in dynamic balance at the time of return-to-sport testing, regardless of their meniscal injury history. In addition to their role in distributing axial joint loads, the menisci provide passive mechanical stability to the knee, contributing secondary restraint to tibial translations both anteriorly and posteriorly.20–22 The lack of an association between meniscal injury history and dynamic balance impairments in this study suggests these deficits may be related more to general neuromuscular factors than residual mechanical insufficiency of the involved limb. It has long been known that detriments to neuromuscular performance and limb asymmetries persist for years after ACL reconstruction and contribute to risk of future injury.11,32 However, the addition of rehabilitation techniques targeting these neuromuscular factors, such as perturbation training, has not resulted in consistent/significant improvements in functional outcomes or return to sport success rates.33 While a longer course of rehabilitation may be effective in mitigating injury risk and improving achievement of evidence-based return to sport criteria,34 an extended return-to-sport timeline may not be a satisfactory solution to many athletes. Thus, further research into emerging/novel surgical and rehabilitation techniques that specifically preserve or enhance neuromuscular function is needed. For example, transcortical direct current stimulation has the potential to impact corticospinal activity and may provide a means to maintain or improve neuromuscular function over the course of recovery after injury or surgical intervention.35
Additionally, surgical repair techniques that seek to preserve native ACL tissue, and potentially the neural elements of the ligament, may allow for greater natural restoration of neuromuscular function. Early studies of techniques such as the bridge-enhanced ACL reconstruction\textsuperscript{56} or other similar approaches have shown promise in the short term.\textsuperscript{57}

While these techniques continue to develop, it is important to recognize there are long-standing treatment approaches with strong evidence that could be examined within a broader neuromuscular context. For instance, electrical stimulation is strongly recommended to enhance quadriiceps strength in the latest clinical practice guidelines from the Orthopedic Section of the American Physical Therapy Association.\textsuperscript{58} However, studies of patients with neurologic disorders have demonstrated the value of functional electrical stimulation to enhance the neural representation of a limb within the central nervous system.\textsuperscript{59} Given that similar neurophysiologic and neurocognitive deficits have been demonstrated in individuals with ACL injury,\textsuperscript{40} use of electrical stimulation, in combination with more conventional rehabilitation components (e.g. targeted strengthening, active isometric muscle contraction), should be considered as a standard of care for more than restoration of simple muscular strength. In addition to augmented sensorimotor stimulation, the environmental context and cognitive-attentional demands of functional and sport-specific tasks should be considered in the rehabilitation plan. A graded exposure approach to the neurophysiologic and neurocognitive demands of patients’ activities may prove to be the most salient, cost-effective means to restoration of multi-system neuromuscular function.\textsuperscript{41}

As with any study, it is important to consider the limitations of this work. First, it should be noted that the current study did not consider the extent or location of meniscal injury. This was also a limitation noted by Clagg et al.\textsuperscript{13} Future studies should examine how the nature/extent of meniscal injury affects neuromuscular performance. In addition, the effect of graft type was not examined as part of this study. Previous studies have compared neuromuscular performance among athletes who received different types of grafts\textsuperscript{6,13}; however, the findings from these studies have been somewhat inconsistent. Also, it is important to note that clinical measures of dynamic balance and hop distance may not be sensitive to subtle differences in postural stability and movement performance. Future studies should consider applying more advanced instrumentation to identify more subtle differences in postural stability and movement control/performance. The relatively low number of athletes (n = 6) who underwent partial meniscectomy should also be considered as a limitation. Although not necessarily surprising, since surgeons typically aim to repair the meniscus when possible, the low number of athletes in this group may have limited our ability to detect subtle between-group differences in dynamic balance and/or hop performance.

Finally, it is worth noting the variability in when athletes were tested (ranging from 5-11 months post-surgery). Dynamic balance and hop test data were recorded at the point of return-to-sport testing, which is typical for studies of this nature.\textsuperscript{13} Since athlete’s progress through rehabilitation at different rates, this resulted in significant variability in the time from surgery to return-to-sport testing. The reason for comparing performance at the point of return-to-sport testing was to ensure that athletes were at a similar stage of recovery, even though they were not necessarily at the same time post-surgery. An alternative would have been to compare performance at a consistent time point (e.g. five months post-surgery); however, this would be problematic since athletes would be at different phases in their rehabilitation (e.g. some would be preparing to return-to-sport, while others would be just beginning to initiate landing/jumping tasks). Regardless, it is interesting to note the variability among athletes with respect to their return-to-sport timeline.

CONCLUSION

The results of this study indicate that adolescent athletes who have undergone ACL reconstruction exhibit deficits in dynamic balance and hop performance for their involved limb, even after completing post-operative rehabilitation. The results of this study also suggest that the magnitude of the inter-limb asymmetries in dynamic balance and hop performance are not dependent on meniscal injury history.

Disclosure

The authors have no conflicts of interest to report.

ACKNOWLEDGEMENTS

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REFERENCES


Agreement Between Isokinetic Dynamometer and Hand-held Isometric Dynamometer as Measures to Detect Lower Limb Asymmetry in Muscle Torque After Anterior Cruciate Ligament Reconstruction

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Keywords: agreement, anterior cruciate ligament reconstruction, hand-held dynamometer, isokinetic dynamometer, limb symmetry index.

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Background
Two commonly used instruments to assess muscle strength after anterior cruciate ligament reconstruction are the isokinetic dynamometer, which measures isokinetic torque and the hand-held dynamometer, which measures isometric torque. Isokinetic dynamometers are considered superior to other instruments but may not be commonly used in clinical settings. Hand-held dynamometers are small, portable, and more clinically applicable devices.

Purpose
The purpose of this study was to assess agreement between a hand-held dynamometer and an isokinetic dynamometer, used to assess lower limb symmetry in knee muscle torque one year after anterior cruciate ligament (ACL) reconstruction.

Study design
Cross-sectional measurement study

Methods
Seventy-two participants who had undergone ACL reconstruction (35 men, 37 women; age= 25.8 ± 5.4 years) were included. Isokinetic muscle torque in knee flexion and extension was measured with an isokinetic dynamometer. Isometric flexion and extension knee muscle torque was measured with a hand-held dynamometer. Bland & Altman plots and Cohen’s Kappa coefficient were used to assess agreement between measurements obtained from the instruments.

Result
Bland & Altman plots showed wide limits of agreement between the instruments for both flexion and extension limb symmetry index. Cohen’s Kappa coefficient revealed a poor to slight agreement between the extension limb symmetry index values (0.136) and a fair agreement for flexion limb symmetry index values (0.236). Cross-tabulations showed that the hand-held dynamometer detected a significantly larger number of participants with abnormal flexion torque limb symmetry index compared to the isokinetic dynamometer.

Conclusion
The wide limits of agreements and Cohen’s Kappa coefficients values revealed insufficient agreement between the measurements taken with the two instruments,

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indicating that the instruments should not be used interchangeably. The hand-held dynamometer was more sensitive in detecting abnormal limb symmetry index in flexion torque, which promotes the option of use of hand-held dynamometers to detect differences between the injured and uninjured leg after ACL reconstruction.

**Level of evidence**

3b

**INTRODUCTION**

Anterior cruciate ligament (ACL) injury is common in athletes, and it is often followed by ACL reconstructions (ACLR). An ACLR is followed by an extensive rehabilitation period and one of the most important rehabilitation goals is to reach symmetric function and strength in the lower limbs.\(^1,2\) Limb asymmetry in strength and function after ACLR can predict an increased risk of reinjury, which in turn increases the risk of early post-traumatic knee osteoarthritis.\(^3-6\) Further, knee extensor muscle weakness has also been suggested to be associated with an increased risk of knee osteoarthritis development and progression.\(^7,8\) Thus, the results of limb symmetry tests are of great importance for clinicians in determining if a patient is fully rehabilitated or ready to return to sport (RTS). Limb symmetry index (LSI) is calculated by dividing the test scores of the injured limb with the uninjured limb multiplied by 100. LSI is typically used to calculate the level of symmetry between the two legs. A LSI >90% is considered satisfactory and is often a criterion before letting a patient RTS.\(^9,10\)

There are a number of functional tests that can be conducted to assess limb symmetry after ACLR. Hop tests, one of the most commonly used functional tests, assess differences in various hopping tasks between the injured and uninjured leg.\(^11,12\) However, LSI measured with hop tests can be overestimated. Barford et al. confirmed this by determining that satisfactory LSI was reached significantly faster with hop tests than with knee extensor muscle symmetry tests.\(^13\) In another study Nagai et al. suggest that muscle strength tests are a better method to evaluate LSI after ACLR since hop tests often result in higher LSI values compared to leg press tests and isokinetic muscle strength tests.\(^14\)

To assess LSI in muscle strength, different measurement instruments can be used. Hand-held dynamometers (HHD) and isokinetic dynamometers (IKD) are commonly used. IKDs are advanced computerized machines measuring isokinetic muscle torque (as a proxy for strength) and HHDs are small portable devices used to measure isometric muscle torque (also as a proxy for strength).\(^15,16\)

IKDs are considered superior compared to other instruments to assess muscle strength, however they are both space-consuming and expensive. Therefore, they are not used commonly in clinics. HHDs, on the other hand are cost-effective, small, and clinically applicable. Previous authors have established the reliability and validity of IKDs and HHDs.\(^16-19\) In a systematic review and meta-analysis Chamorro et al. established the reliability and concurrent validity of a HHD and IKD in measuring muscle strength in the knee, hip, and ankle joint. Their results revealed low reliability for knee extension and ankle plantar flexion strength when measured with an HHD. Additionally, the results showed a high correlation between the measurements from the instruments for hip strength values and a moderate correlation for knee and ankle strength values.\(^16\) Lesnak et al. assessed the agreement between the two instruments measuring isometric quadricep strength in a healthy population. Their results showed that the HHD produced higher peak torque strength values as compared to those from the IKD.\(^17\) In a more recent study, Hirano et al. established high validity (r=0.78) and intra-rater reliability comparing the results of knee extension muscle strength measured with a belt stabilized HHD to an IKD (ICC\(_1\),\(^1=0.75\)).\(^18\) However, Toonstra et al. concluded that significant differences were found in peak torque strength values observed between isometric knee flexion and extension measured using IKD and HHD.\(^19\)

To the knowledge of the authors, no previous studies have assessed agreement or sensitivity in detection of abnormal LSI between LSI values calculated from isokinetic strength tests measured with an IKD and isometric strength tests measured with an HHD. Isokinetic strength measures are commonly used in research while HHDs are more commonly used clinically, highlighting the importance of comparing these instruments. In addition, the instruments should be studied in subjects who have undergone ACLR, as this a patient group where lower limb strength tests are frequently used to assess both progress in rehabilitation and to make clinical decisions regarding RTS. Thus, the purpose of this study was to assess agreement between a hand-held dynamometer and an isokinetic dynamometer, used to assess lower limb symmetry in knee muscle torque one year after ACLR. In addition, the authors investigated which of these two instruments was superior in detecting limb asymmetry. It was hypothesized that the agreement between the two types of strength measurements is low and that the IKD would be superior in detecting individuals with an LSI <90.

**METHODS**

**DESIGN**

A cross-sectional study assessing agreement between two different measurement instruments adhering to the STROBE guidelines (https://www.strobe-statement.org/).

**STUDY CONTEXT**

This study is an exploratory analysis of baseline data from an ongoing prospective cohort study aiming to assess the correlation between lower limb function and early post-traumatic osteoarthritis after ACLR.\(^20\) Participants were
consecutively recruited from the department of orthopedics, Skåne University Hospital. All patients who had undergone an ACLR during the time period January 2017–February 2019 were asked to participate via letter. Inclusion criteria were i) one year (10-16 months) after ACLR, with or without associated injuries to other knee structures, ii) age between 18-35 years. Exclusion criteria were i) previous serious injury or surgery to either knee, ii) other diseases or disorders affecting lower extremity function (e.g., hernia). The present study has received ethical approval from the Swedish Ethical Review Board (Dnr 2017/916). The participants received a letter with information of the study and gave their written consent before participating in the study. All participants were informed that they were allowed to cancel their participation in the study at any time.

DATA COLLECTION

Baseline data for the prospective cohort study was collected between March 2018 and March 2020. One physiotherapist (AC) collected all data. Demographic data (age, height, weight, type of ACL graft) was collected prior to the testing. Before executing the tests, all participants performed a five-minute warm up on an ergometer bicycle. The HHD torque measures were performed first and then the IKD assessments for all participants, allowing for a rest period of at least five minutes in between.

HAND-HELD DYNAMOMETER

Isometric knee extension torque was measured with a HHD (Power Track II Commander Echo; JTECH Medical, Salt Lake City, Utah, USA) with the participants sitting on a treatment table with their knee in 90° flexion and their thighs fixated to the treatment table with a strap. Another strap was used around the leg of the treatment table and the HHD, which was placed on the anterior side of the participants’ distal tibia. The participants were asked to extend their knee with maximal effort.

Isometric knee flexion torque was tested with the participants lying on their stomach on a treatment table with their knee in 90° flexion. The examiner was sitting on the end of the table with a strap around the pelvis and around the HHD placed on the posterior side of the participants’ distal tibia. The pelvis and the leg that was not being tested were fixated to the treatment table with two straps. The participants were asked to flex their knee with maximal effort. When testing isometric extension and flexion torque with the HHD each test was repeated three times and the participants were asked to hold each maximal contraction for five seconds with 15 seconds of recovery between the contractions. The peak torque (N) of three measurements with each leg was collected and then normalized to body mass (N/kg×100). To randomize and avoid learning affects the right leg was always tested first.20

ISOKINETIC DYNAMOMETER

Isokinetic concentric torque in knee flexion and knee extension was measured in 60 degrees/sec with a Biodex (Medical Systems, Shirley, New York) with the participants in a sitting position with their arms across their chest. The chest, pelvis and thigh were secured with straps. The Biodex was calibrated before each test and the starting position of the knee was 90° flexion. The test was performed in a range of motion of 0-90° knee flexion. Four trial repetitions were performed with submaximal effort. After this, the participants performed five maximal contractions with each leg, starting with the non-injured leg. The peak value of the five trials for each leg was recorded. The measurements were presented as peak torque, expressed in Newton-meters (Nm) and then normalized to body mass, (peak torque divided by the participants’ body weight in kg (Nm/kg)).

DATA ANALYSIS

Descriptive statistics with mean and standard deviation was used for presentation of demographic data such as weight, height, age, and body mass index (BMI). Analysis of agreement was performed in The Statistical Package for Social Sciences (SPSS), (Version 26.0 IBM Corp). Normalized peak torque values of extension and flexion strength of the injured and uninjured leg were used to calculate LSI.

Bland & Altman plots with 95% limits of agreement (LOA) (average difference between measurement instruments ± 1.96 x SD of the difference) and Cohen’s Kappa coefficient were used to assess agreement between the two measurement methods. The results of Bland & Altman plots give a visual representation of the difference between the mean of two different measurement methods used on the same subject, which in this case is the IKD and HHD, and shows systematic differences.21 The following thresholds for Cohen’s Kappa coefficient were used; <0.00 no agreement, 0.00-0.20 poor to slight agreement, 0.21-0.40 fair agreement, 0.41-0.60 moderate agreement, 0.61-0.80 substantial agreement, 0.81-1.00 almost perfect agreement.22

To measure which instrument was superior in detecting lower limb asymmetry in muscle strength the participants were divided into two different groups. One group included the participants with a LSI>90% and the other group included participants with a LSI<90%. After this, cross tabulations with abnormal LSI (LSI>90%) and normal LSI (LSI90%) were constructed. McNemar’s test was used to test the proportion of participants with normal versus abnormal LSI values for the HHD and IKD in flexion and extension strength. Statistical significance was set at p<0.05.

RESULTS

Seventy-two (37 women; age= 25.8 ± 5.4 years), were included in this study (Table 1 and Figure 1).

Of the 73 participants originally included, one of the participants experienced discomfort during the extension strength test with the HHD and did not proceed with this test but performed all flexion strength tests. Data for another participant were lost for both knee flexion and extension strength due to technical problems with the Biodex,
Table 1. Participant characteristics (n=72)

<table>
<thead>
<tr>
<th></th>
<th>Age (y), mean (SD)</th>
<th>Women (n,%),</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI (kg/m2), mean (SD)</th>
<th>Injured knee n (%),</th>
<th>Associated injuries n (%),</th>
<th>Type of graft n (%),</th>
<th>Time since ACLR (months), mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25.8 (5.4)</td>
<td>37 (51.4)</td>
<td>174.0 (8.7)</td>
<td>75.7 (14.3)</td>
<td>24.9 (4.0)</td>
<td>22 (31)</td>
<td>62 (86)</td>
<td>62 (86)</td>
<td>12.3 (1.4)</td>
</tr>
</tbody>
</table>

y years, SD standard deviation, n number of participants, BMI body mass index

leaving 72 (flexion strength) and 71 (extension strength) participants, respectively, for the analysis.

Overall, the participants had a higher mean peak torque value in their uninjured leg compared to their injured leg in both isokinetic and isometric strength. Generally, the peak torque value measured with the IKD was higher than the peak torque value measured with the HHD. The mean LSI measured with the HHD was 75.3 % for flexion and 94.6% for extension. The mean LSI measured with the IKD was 91.3% for flexion and 87.7% for extension (Table 2).

The Bland & Altman plots for both extension and flexion LSI-values revealed wide limits of agreement (Figures 2 and 3). Cohen’s Kappa coefficient was low for both extension LSI values (0.136) and for flexion LSI values (0.236) indicating a poor to slight respectively a fair agreement between the instruments.

The cross tabulations showed that the HHD detected significantly more participants with abnormal flexion torque LSI compared to the IKD (59 vs 35, p<0.001) (Table 3) whereas there was no statistically significant difference for extension torque LSI (HHD 29, IKD 58, p=0.150) (Table 4).

DISCUSSION

The purpose of this explorative analysis was to assess measurement agreement between an IKD and a HHD, used to detect lower limb asymmetry in flexion and extension knee muscle torque after ACLR. In addition, the aim was to investigate which of these two instruments was superior in detecting lower limb asymmetry. In support of the hypothesis, the results of this study showed that the measurement agreement between the instruments is low, indicating that the HHD and IKD should not be used interchangeably. In addition, contrary to the hypothesis, the HHD detected a significantly larger number of participants with abnormal flexion LSI than the IKD.

The different types of strength, at different angles that the instruments measure may explain the low agreement between the LSI values. As previously mentioned, the IKD measures isokinetic torque whereas the HHD measures isometric torque. Isokinetic torque is assessed during a contraction of the muscles at a constant speed in a specific ROM, implying that the muscle length is changing. Isometric torque is a static strength assessment inferring that the muscle remains contracted at specific joint angle and the length of the muscle does not change. 15,16,23 Since peak torque (strength) values were the values used to calculate

![Figure 1. Flow chart of participants](image-url)
Table 2. Mean peak torque value (SD/SE) (% of body weight) for injured leg (inj) and uninjured leg (uninj), mean difference (diff) in peak torque value (with 95% CI) between injured and uninjured leg. Mean of limb symmetry index (LSI, %) of torque measured with HHD and IKD, mean difference between HHD LSI-values and IKD LSI-values.

<table>
<thead>
<tr>
<th></th>
<th>Peak torque HHD Inj</th>
<th>Peak torque IKD Inj</th>
<th>Peak torque HHD Uninj</th>
<th>Peak torque IKD Uninj</th>
<th>Injured vs uninjured HHD</th>
<th>Injured vs uninjured IKD</th>
<th>LSI% HHD</th>
<th>LSI% IKD</th>
<th>HHD vs IKD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexion</strong></td>
<td>62.8 (21.6/2.5)</td>
<td>111.0 (29.6/3.5)</td>
<td>83.0 (18.7/2.2)</td>
<td>121.4 (26.5/3.2)</td>
<td>-45.3 (-61.4;-31.2)</td>
<td>-10.4 (-19.6;-1.2)</td>
<td>75.3 (17.1/2.0)</td>
<td>91.3 (12.5/1.5)</td>
<td>-16.0 (-21.0;11.1)</td>
</tr>
<tr>
<td><strong>Extension</strong></td>
<td>182.0 (54.3/6.4)</td>
<td>222.1 (58.1/6.8)</td>
<td>197.3 (64.7/7.6)</td>
<td>194.7 (58.1/6.8)</td>
<td>-29.7 (-75.4;16.1)</td>
<td>-30.3 (-49.4;-11.2)</td>
<td>94.6 (18.8/2.2)</td>
<td>87.7 (20.9/2.5)</td>
<td>6.9 (0.3;13.5)</td>
</tr>
</tbody>
</table>

SD standard deviation, SE standard error, CI confidence interval, HHD hand-held dynamometer, IKD isokinetic dynamometer
LSI in this study, it is most likely that the isokinetic muscle torque peak torque value was reached at different joint angles (between 0°-90° flexion) in the knee joint. On the contrary, the isometric flexion and extension torque was only tested at 90° of flexion in the knee joint. Emami et al. found that isometric flexion torque measured at 90° and 100° of flexion was significantly reduced (compared prior to surgery) one year after ACLR. The same study showed that flexion torque was not significantly reduced at 20° and 45° of flexion. This is also supported by the mean peak torque value presented in this study, since the HHD measurements revealed generally lower peak torque value in both flexion and extension strength. This may imply that if the isometric torque would have been tested at different angles and the highest peak torque value across the range would be used in the data analysis of this study it could have affected the LSI value and thus, also the agreement between the instruments.

In this study, agreement and sensitivity for both knee flexion and knee extension torque were assessed. Several studies and systematic reviews have concluded that weakness in extensor muscles is associated to development of osteoarthritis, reduced quality of life and functional disabilities, highlighting the importance of regaining extensor strength after ACLR. In Sweden the majority of patients undergoing ACLR receive a hamstring tendon graft. Studies show that patients who receive a hamstring graft have a remaining weakness in flexion strength two years after ACLR. Taken together, this emphasizes the importance of detecting both knee extension and flexion strength deficits after ACLR. The results of this study revealed that the HHD detected almost twice as many participants with abnormal flexion strength LSI compared to the IKD, whereas there was no significant difference between the instruments for extension strength LSI. These results highlight the potential use of isometric measurement instruments to assess knee flexion torque asymmetries in ACLR patients.

As discussed above, the IKD is popular, especially in sports medicine and research. One reason that the IKD is considered superior to the HHD is that IKDs are not affected by the strength differences between the patient and the examiner holding the dynamometer. Further, the IKD has been criticized since patients do not always reach maximum strength performance in the IKD if they are not familiar with the equipment and know how it works. Other limitations with the IKD include the costs and the limited availability in clinics. However, although both instruments have limitations, the high incidence of ACL re-injuries imply that the functional tests are not sufficient to assure readiness to RTS. Muscle strength tests could thus be a good complement to the functional tests. The results of the current study showed that the HHD at 90° of knee flexion identified more patients with abnormal flexion LSI one year after ACL and promote the clinical use of HHDs. Further studies may reveal if there are any strength measures that are superior in detecting deficits in knee extension LSI.

STRENGTHS AND LIMITATIONS
One of the strengths of this study is the large sample which increases the chance of accurate results. Another strength of this study is that the same researcher performed...
Figure 3. Bland and Altman plot with 95% limits of agreement (LOA) for limb symmetry index (LSI) of flexion muscle torque.

The differences in LSI between muscle torque measured with a HHD and an IKD plotted against their mean LSI. Mean difference -16.01 (95% LOA -51.19 to 19.17)

Table 3. Cross tabulation of the proportion of normal LSI (LSI>90%) and abnormal LSI (LSI<90%) between the two measurement methods (HHD and IKD) measuring flexion torque.

<table>
<thead>
<tr>
<th>LSI Flexion torque HHD</th>
<th>LSI Flexion torque IKD</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSI&lt;90%</td>
<td>LSI&lt;90%</td>
<td>33</td>
</tr>
<tr>
<td>LSI&gt;90%</td>
<td>LSI&gt;90%</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>72</td>
</tr>
</tbody>
</table>

LSI Limb symmetry index, HHD hand-held dynamometer, IKD isokinetic dynamometer

Table 4. Cross tabulation of the proportion of normal LSI (LSI>90%) and abnormal LSI (LSI<90%) between the two measurement methods (HHD and IKD) measuring extension torque.

<table>
<thead>
<tr>
<th>LSI Extension torque HHD</th>
<th>LSI Extension torque IKD</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSI&lt;90%</td>
<td>LSI&lt;90%</td>
<td>18</td>
</tr>
<tr>
<td>LSI&gt;90%</td>
<td>LSI&gt;90%</td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>71</td>
</tr>
</tbody>
</table>

LSI Limb symmetry index, HHD hand-held dynamometer, IKD isokinetic dynamometer

all data collection to avoid inter-rater variability. Further, in contrast to other studies, the current study compared muscle strength LSI values in injured subjects who went through ACLR. Previous studies have only compared peak torque strength values in healthy subjects. To assess which instruments should be used clinically for strength assessment in ACLR rehabilitation it is important that they have been tested in participants who have undergone ACLR.

One major limitation of this study is that agreement between two instruments that measures different types of strength (isometric vs. isokinetic) was assessed. This may imply that there may not be a good agreement between the two instruments. However, in this study LSI values were used in the data analysis for agreement. The LSI values are independent of both demographic factors and what type of strength that is tested since the variable is a ratio between the participants' injured and uninjured leg. This means that...
it is not the instruments per se that are compared against each other, but the LSI values. Also, to avoid bias associated with gravitational forces, only isometric torque at 90° of knee flexion was assessed, which may have contributed to the poor agreement between measurements. It may further be argued that 90° of knee flexion is not a functional position with regards to knee injury risk. Although, in a recent study Beere et al. confirmed that testing isometric quadriceps strength with a dynamometer is dependent on the angle of the knee joint and that quadriceps strength should be tested in either 90° or 30° of flexion to detect asymmetries similar to the IKD, future studies investigating if strength deficits, assessed in 90° of knee flexion, are associated with relevant outcomes, such as RTS and risk of second injuries are warranted. Due to practical reasons, isometric knee flexion torque was assessed in a prone position, whereas the isokinetic knee flexion torque was assessed in a seated position, according to the IKD standardization. Although a prone position is proposed to be more functional, the difference in testing position may constitute another reason for the lack of agreement in the current study.

Furthermore, LSI presumes that the strength and function in the uninjured leg corresponds to the patient’s strength and function in the injured leg before the ACL injury. However, the ACL injury may also affect the strength and function of the uninjured limb due to general deconditioning and/or arthrogenic muscle inhibition. It is therefore possible that the LSI is overestimated when assessing lower limb muscle strength. However, studies show that patients who return to sport before they have reached a satisfactory LSI have an increased risk of early development of osteoarthritis and lower self-perceived function in the knee, implying that LSI, despite criticism, is a useful measure. Finally, since this was an exploratory analysis of an ongoing longitudinal trial, no a priori power calculation was performed. However, since the sample size in the current study is more than twice the recommended sample size of 32 participants for agreement studies, the sample should be adequate for the purpose of this study.

CONCLUSION

The wide limits of agreements and low Cohen’s Kappa coefficients in this study, indicate a poor agreement between IKD and HHD implying that the instruments should not be used interchangeably for measurements of strength after ACLR. The hand-held dynamometer at 90° of knee flexion was more sensitive in detecting abnormal limb symmetry index in knee flexion strength. However, future research is needed to determine which type of instrument is superior in detecting deficits in knee extension strength and if strength deficits in 90° of knee flexion are associated with relevant ACLR outcomes, such as RTS and re-injury risk.

CONFLICTS OF INTEREST

The authors report no conflicts of interest related to this manuscript

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An Anterior Cruciate Ligament (ACL) Injury Risk Screening and Reduction Program for High School Female Athletes: A Pilot Study

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Keywords: anterior cruciate ligament, female athletics, injury, screening

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Background
Anterior cruciate ligament (ACL) injury causes physical, mental, and financial burdens. Therefore, it is imperative to screen, identify, and educate athletes who are at high-risk. The combination of screening and education could identify those at risk and potentially reduce future injuries.

Purpose
The purpose was to conduct a feasible community pre-season screening program for high school female athletes for the presence of known modifiable risk factors that predispose them to sustaining a non-contact ACL injury.

Study Design
Non-experimental prospective study

Methods
A convenience sample of 15 healthy female athletes were recruited from local high schools, consisting of 11 soccer players and four basketball players. A pre-season screening program was designed encompassing four stations that addressed modifiable neuromuscular and biomechanical risk factors including range of motion (ROM), jump-landing technique, strength, and balance. Athletes were categorized into high-risk versus low-risk groups based on cutoff scores previously established in the literature.

Results
Every athlete met the high-risk cutoff score for at least one extremity during the ROM screening, and some met high-risk cutoff scores for more than one ROM. Out of all four categories tested, lower extremity ROM demonstrated the greatest deficits.

Conclusion
This study identified athletes as having multiple modifiable risk factors that can be addressed with training and exercises. This supports implementing a pre-season program aimed at screening for injury risk factors.

Level of Evidence
Level 3
INTRODUCTION

The anterior cruciate ligament (ACL) connects the femur to the tibia and plays a key role in stabilizing the knee in both the sagittal and transverse planes which include anterior tibial translation and rotational loads, respectively.1 Approximately 70% of ACL injuries occur by noncontact mechanisms, such as when the athlete is changing directions, slowing down at near or full knee extension, or landing from a jump.1,2 There is an estimated 200,000 ACL-related injuries a year with 100,000 requiring reconstructive surgery.3 The average cost of ACL reconstruction is $24,707, making the total annual cost approaching $2.5 billion.4 ACL injuries are common in adolescent female athletes often resulting in long-term physical, mental, and financial burdens.5

Female adolescents participating in jumping and pivoting sports have a two to nine time greater chance of experiencing an ACL injury versus male athletes of the same age and sport.2 In female high school athletes, knee injuries are the most common disability accounting for nearly 91% of season-ending injuries.5 Additionally, year-round female soccer and basketball athletes have a 5% chance of tearing their ACL every year they participate in sports.5 ACL incidence rate for soccer athletes ranges from 0.06 to 5.7 per 1000 hours of active play including practice and games.2 Approximately 50% of ACL injuries have associated concomitant injuries which include the medial collateral ligament (MCL) and medial meniscus.5

ACL injury risk factors are multifactorial, including non-modifiable and modifiable factors. Non-modifiable anatomical and hormonal factors, such as a wider Quadriceps-angle (Q-angle) or the release of estrogen and relaxin, cannot be influenced by physical therapy intervention. Although non-modifiable factors cannot be addressed by exercise intervention, they provide further insight and create an encompassing profile of at-risk athletes. For example, an increased Q-angle could result in altered biomechanical hip internal rotation (IR) and knee valgus, which could increase patellofemoral joint stress and instability.6 However, biomechanical abnormalities and neuromuscular recruitment, such as poor postural positioning or proximal stability, can be modified with appropriate training and provide the greatest impact on reducing the risk of noncontact ACL injuries.2

Abnormal positioning and irregular movement patterns, as well as strength imbalances, can predispose an athlete to a higher risk of ACL injury. A movement pattern known as dynamic valgus, is an associated biomechanical risk factor during performance of agility and plyometric physical activities such as planting, cutting, or jumping.1,5 Dynamic valgus includes hip adduction and internal rotation (IR), tibial external rotation (ER), and ankle eversion, which result in increased joint reaction force in the lateral compartment of the knee and increased strain on the MCL. Hip abductor weakness is a contributing factor to dynamic valgus biomechanics at the knee.1,5 A stronger lateral quadriceps and weaker medial hamstring (HS) strength leads to quadriceps dominance. This neuromuscular imbalance pre-disposes the risk of ACL injury due to increased stress placed on the ACL.7

Since the passage of Title IX, the number of female athletes participating in high school and college sports has increased 10- and five-fold, respectively.5 Over the past twenty years, the speed, power, and aggressiveness of female athletes have drastically increased which has resulted in a greater number of musculoskeletal injuries.5 Overall, ACL injury risk is multifactorial which includes non-modifiable anatomical and hormonal risk factors, as well as modifiable biomechanical and neuromuscular risk factors that can be positively affected by appropriate screening and conditioning.

Physical therapists (PTs) have a role in injury prevention and should design and develop screening programs aimed at preventing injury as a part of a wellness-focused initiative for community health.8 Additionally, PTs should focus on engaging with the community and offer preventative and screening services to reduce the need for costly management following an injury.9 The cost of potential screening programs has been found to range from $2.00 to $15.00 per player, depending on the equipment and personnel used; whereas, the cost of an ACL reconstruction can cost upwards of $17,000.10 Screening programs have been estimated to reduce the incidence of ACL injury by an average of 40%, resulting in an improvement of health outcomes.10 In the literature, the majority of ACL screening programs focus on one risk factor in isolation, such as range of motion.11,12 Currently, there are no existing protocols that combine several modifiable risk factors into an all-inclusive ACL injury screening program. The purpose was to conduct a feasible community pre-season screening program for high school female athletes for the presence of known modifiable risk factors that predispose them to sustaining a non-contact ACL injury.

MATERIALS/METHODS

The study was approved by the Institutional Review Board of Walsh University prior to completion and data collection (#2021007).

STUDY DESIGN AND PARTICIPANTS

This study was a non-experimental, prospective pilot study of high school female soccer and basketball athletes. Inclusion criteria were female soccer and basketball athletes, aged 13-18 years old. None of the participating athletes had undergone knee surgery nor were recovering from any lower extremity injury. A convenience sample was utilized by contacting local coaches through email to provide information regarding the screening program and to inquire about volunteer recruitment. All athletes completed a medical history form prior to starting the program. All athletes and parents were informed of the purpose and components of the program, and all athletes and parents provided assent and consent, respectively, for participation in the program due to the study involving minors.
INTERVENTION PROCEDURES

Each athlete progressed through the pre-season screening program in the following order: range of motion, jump landing assessment, strength testing, and dynamic balance testing. The sequencing of performing the screening measures promoted reliability of testing procedures and limited the effects on performance for subsequent tests.15 Because of test sequencing, rest in between each station was not deemed necessary, allowing for increased efficiency of the screening program. All screening measures were performed by student physical therapists (SPT’s), who were previously educated on the below measures. Ten SPTs completed 30-minutes of instruction, training, and practice for their respective measures. Throughout the entire program, all outcomes were assessed by the same SPTs. The screening program and educational presentation provided to the coaches were reviewed and supervised by licensed PTs. Prior to completing the screening stations, athletes completed a five-minute warm-up on an upright exercise bike.

OUTCOMES/TEST PROTOCOL

The primary outcomes of this program included range of motion, jump landing strategy, muscle strength, and single-leg dynamic balance.

RANGE OF MOTION

A goniometer was used to measure the passive range of motion (PROM) of hip IR, hip ER, weight-bearing ankle dorsiflexion (DF), and the Q-angle. The reliability of PROM goniometric measurements for the lower extremity is considered good to excellent.14 The standard error of measure (SEM) reported in the literature for the four measurements utilizing a goniometer are as follows: 2.42 degrees for hip IR, 2.53 degrees for hip ER, 1.8-2.8 degrees for weight-bearing ankle DF, and 1.02 degrees for Q-angle.15–17 The same testing positions described below were the same testing positions utilized in the articles where the SEMs were reported.15–17 However, the populations of the articles where the SEMs were reported were different from the target population of female high school athletes. For hip IR and hip ER, the population was comprised of individuals with femoral acetabular impingement compared to healthy controls.15 For weight-bearing ankle DF, the population was healthy young adults with an average age of 24 years old.16 For Q-angle, the population consisted of females and males between the ages of 21–50 years.17 Currently, there is a lack of literature on reporting SEM for the female adolescent population.

To measure hip IR and ER PROM, the athlete was supine on the treatment table with the hip and knee of the measured leg flexed to 90° and the non-measured leg fully extended on the table.11 The examiner lined up the stationary arm of the goniometer with the tibial tuberosity and then passively took the flexed hip into both IR and ER.11 The examiner moved the moveable arm of the goniometer to align with the tibial tuberosity while keeping the stationary arm in its vertical position (Figures 1 and 2).11 This was completed three times on each lower extremity and the average of each side was recorded.

To measure weight-bearing ankle DF, the athlete was asked to stand with the ankle being measured perpendicular to the wall with the second toe and midline of the foot placed directly on a piece of tape placed on the floor.12 The athlete was then instructed to lunge the knee towards
the wall until their maximal ankle DF was reached, which was indicated when the heel lifted off the ground.\textsuperscript{13} If the athlete’s knee contacted the wall before maximal DF was achieved, their foot was moved posteriorly.\textsuperscript{12} The axis of the goniometer was placed below the lateral malleolus, the stationary arm was in line with the 5\textsuperscript{th} metatarsal, and the moveable arm was in line with the fibular head. This was completed three times on each lower extremity and the average of each side was recorded (Figure 3).

To measure the Q-angle, the athlete stood in anatomical position without shoes and socks. The examiner placed the axis of the goniometer at the center of the patella and aligned the stationary arm of the goniometer with the ipsilateral ASIS.\textsuperscript{18} Next, the examiner aligned the moveable arm of the goniometer with the tibial tuberosity (Figure 4). The intersection of the line drawn from the ASIS to the center of the patella and the line drawn from the center of the patella to the tibial tuberosity is considered the Q-angle.\textsuperscript{18} This was completed three times on each lower extremity and the average of each side was recorded.

\textbf{JUMP LANDING STRATEGY}

Jump landing was analyzed using the Landing Error Scoring System (LESS). The athlete stood on a 30 cm (12 in) box. A taped line that marked 50\% of their height was positioned in front of the box. The athlete began the test standing on the box and was instructed to jump in front of the taped line followed by jumping as high as they could immediately upon landing. The test was repeated for a second trial with a minute-long break in between. Each trial was video-taped using iPads (Apple, Cupertino, CA) – in both frontal and sagittal views – and analyzed with the Hudl application (Hudl, Lincoln, NE). Hudl allowed for slowing down the videos and applying virtual angles to each frame. This test utilizes a 17-category scoring system to rate jump landing characteristics.\textsuperscript{19} Quality of jump landing mechanics are classified into four categories: ≤ 4 errors is rated as excellent, > 4 to ≤ 5 errors is rated as good, >5 to ≤ 6 errors is rated as moderate, and > 6 errors is rated as poor.\textsuperscript{20} Females commonly score lower than males, with one study finding that only 14\% of the female participants were classified in the excellent category, compared to 29\% of males scoring within the excellent category.\textsuperscript{20} College-aged athletes have been found to have lower scores on the LESS compared to their high school-aged counterparts (4.42 and 5.36 respectively); however, these reported scores combined both males and females.\textsuperscript{21} There are currently no studies reporting youth female LESS scores in isolation to determine normative values for this population. Research has demonstrated adequate interrater and intrarater reliability of the LESS test with intraclass correlation coefficient values of 0.84 and 0.91 respectively.\textsuperscript{20} Validity of the LESS was item-dependent when comparing the results with the “gold standard” of three-dimensional motion analysis and ranged from poor (10\%) to excellent (100\%).\textsuperscript{22}

\textbf{MUSCLE STRENGTH}

A handheld dynamometer (HHD; Hoggan Scientific Micro-FET2, Salt Lake City, UT) utilizing stabilization belts was used to assess hip ER, hip abduction, knee flexion, and knee extension strength. Proximal body segments were stabilized using external support via stabilization belts. For each strength measurement, the athlete was prompted to perform a make-contraction which consisted of a two-second ramp-up time followed by a five-second maximal contrac-
Figure 5. Measurement of hip external rotation strength.

Figure 6. Measurement of hip abduction strength.

tion. After five seconds, the athlete relaxed, and data was recorded. This was completed three times on each lower extremity and the average of each side was recorded. The belt stabilized HHD displayed moderate to excellent inter-examiner reliability for measuring hip and knee muscle groups and was moderately to highly correlated with the isokinetic dynamometer. While the ideal method would be to use an isokinetic dynamometer, it is expensive, lacks portability, and requires expert training. An HHD has proven to be an appropriate alternative that is inexpensive, portable, and easy to use.

To measure hip ER strength, the athlete sat at the edge of a treatment table and a belt was positioned at the proximal thighs and secured around the table to stabilize the legs. The knees were bent to 90°, and the HHD was placed proximal to the medial malleolus. The examiner stood medial to the test extremity when measuring strength (Figure 5). Hip ER strength measures were recorded in kilograms (kg) and expressed as a percentage of body weight (BW).

To measure hip abduction strength, the athlete was side lying on a treatment table, and a belt was positioned around the waist proximal to the iliac crest and secured around the table to stabilize the pelvis. The hips were in neutral meaning no forward or backward rotation, neutral lumbopelvic positioning, and no hip extension or flexion. The HHD was placed 10 cm proximal to the lateral femoral epicondyle. The examiner stood posteriorly to the athlete when testing to ensure neutral alignment of the pelvis (Figure 6). Hip abduction strength measures were recorded in kg and expressed as a percentage of BW.

To measure knee flexion strength, the athlete was prone on a treatment table and two blue foam pads (Airex, Switzerland) were placed underneath their stomach to promote hip flexion for more optimal HS length-tension. With increased hip flexion, there is a greater knee flexion torque and a better replication of stride position in gait. A belt was positioned proximal to the iliac crest and secured around the table to stabilize the pelvis. The HHD was placed proximal to the Achilles tendon, and the examiner stood at the end of the table in line with the athlete. The make-contraction was performed into knee flexion of approximately 60° (Figure 7). Knee flexion strength measures were recorded in kg and expressed as a hamstring to quadriceps (H:Q) strength ratio.

To measure knee extension strength, the athlete was sitting at the edge of a treatment table and a belt was positioned at the proximal thighs. The knees were bent to 90°, and the HHD was placed at the anterior lower leg proximal to the ankle. The examiner held the HHD in position by placing their elbows in their abdomen with their back against the wall to provide a more stable barrier (Figure 8). Knee extension strength measures were recorded in kg and expressed as an H:Q strength ratio.

SINGLE LEG DYNAMIC BALANCE

Dynamic balance was measured by assessing the quality of movement during a lateral step-down test (LSD). Athletes performed the LSD from a 6-inch step and quality of movement was visually assessed using a scale with scores ranging from 0 to 6. Using this scale, a total score of 0 or 1 is classified as "good" quality of movement, 2 or 3 is "moderate" quality, and 4 or above is "poor" quality. Scoring was based on five criteria: 1) Arm strategy. If the subject removed a hand off their waist during the test, 1 point was added; 2) Trunk movement. If the trunk leaned to any side,
became unsteady (i.e. wavers from side to side on the tested side), add 1 point. 28

Using the previously mentioned scale of measurement, several studies have found the interrater reliability to be substantial (Kappa Coefficient \( K = 0.67 \) & \( K = 0.81 \)) 28,29 for the LSD in females diagnosed with patellofemoral pain syndrome and moderate \( K = 0.59 \) 30 for healthy females. These values indicate a moderate to excellent level of agreement which is considered suitable for use in clinical practice. Validity has not been specifically mentioned in the literature for the LSD; however, studies have shown that altered movement patterns that lead to excessive knee valgus alignment, as measured by the LSD, have been implicated as a risk factor for lower extremity injuries including non-contact ACL injuries. 30,31 There is an association between decreased quality of movement on the LSD and decreased ankle dorsiflexion ROM. 30 Females who demonstrate decreased dorsiflexion during the LSD exhibit other altered movement patterns associated with ACL injury: increased frontal plane hip motion, increased transverse plane knee motion, and decreased sagittal plane knee motion. 31

Athletes were asked to remove shoes and socks prior to the test, and a sticker was placed on the athlete’s tibial tuberosity to help with visualization during the test. 28 A second sticker was placed on the step just under the athlete’s second toe once they assumed the starting position to aid examiners with scoring. 28 A verbal explanation of the procedure was given to the athlete, followed by a demonstration. Athletes performed five practice repetitions, followed by five consecutive test repetitions that were scored. 28 The LSD was evaluated by two examiners simultaneously, and after scoring the test, both examiners came to a consensus on the final score that was recorded. This process was then repeated for the contralateral leg.

RESULTS

A total of 15 female athletes participated in the screening program (Table 1). Athletes were considered to be at a higher risk of injury when meeting the cutoff score on at least one lower extremity. Group means were calculated for each variable, excluding the measurements for hip ER and abduction strength (Figure 9). These measures were excluded due to the normalization of the data based on each individual athlete’s weight.

Table 1. Athlete demographics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Soccer (n=11)</th>
<th>Basketball (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>14.46 ± 0.92</td>
<td>15.75 ± 0.96</td>
</tr>
<tr>
<td>Height (in)</td>
<td>64.36 ± 2.94</td>
<td>66.5 ± 1.73</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>58.06 ± 11.03</td>
<td>64.66 ± 8.15</td>
</tr>
</tbody>
</table>

Values shown as mean ± standard deviation
Abbreviations: in, inches; kg, kilograms

1 point was added; 3) Pelvis plane. If the pelvis rotated or elevated one side compared with the other, 1 point was added; 4) Knee position. If the knee deviated medially and the tibial tuberosity crossed an imaginary vertical line over the 2nd toe, add 1 point, or, if the knee deviated medially and the tibial tuberosity crossed an imaginary vertical line over the medial border of the foot, add 2 points, and; 5) Maintain steady unilateral stance. If the subject stepped down on the non-tested side, or if the subject’s tested limb

Figure 7. Measurement of knee flexion strength.

Figure 8. Measurement of knee extension strength.
Figure 9. Group means and standard deviation for range of motion, jump landing, strength, and single-leg dynamic balance measures.

Abbreviations: DF, dorsiflexion; ER, external rotation; H, hamstring; IR, internal rotation; L, left; LESS, landing error scoring system; LSDT, lateral step-down test; Q, quadriceps; R, right

RANGE OF MOTION

Hip ER below 30° or a combined measurement of hip IR and ER below 75° is correlated with a higher risk of ACL injury.11 In this sample, 13/15 athletes would be considered at a higher risk of injury due to lack of internal rotation; and when examined for total hip rotation, 11/15 athletes would be considered at a higher risk of injury (Table 2). Weighted ankle DF below 41° has been correlated with a higher risk of ACL injury.12 This measurement was most prevalent in the sample with every athlete meeting the high-risk cutoff score in at least one lower extremity (Table 2). Q-angle of greater than 19° has also been correlated with a higher risk of ACL injury.13 Only one athlete was found to have met this cutoff score (Table 2).

JUMP LANDING STRATEGY

A score of five or greater on the LESS has been correlated with an increased risk of ACL injury (sensitivity = 86%, specificity = 64%).19 The LESS results indicate that 10/15 athletes met the high-risk cutoff score (Table 3). The most common suboptimal landing characteristics were lack of adequate knee flexion at initial contact and excessive medial knee displacement at both initial contact and at the point of maximal knee flexion.

MUSCLE STRENGTH

Hip ER strength of ≤20.3% of body weight or a hip abduction strength of ≤35.4% of body weight has been correlated with an increased risk of ACL injury.25 For hip ER strength, 13/15 athletes met the high-risk cutoff score (Table 4). For hip abduction strength, 5/15 athletes met the high-risk cutoff score (Table 4).

Previous authors have suggested that a H:Q strength ratio of less than 60% was linked with a higher risk of ACL injury.32 For H:Q ratio, 10/15 athletes met the high-risk cutoff score with a higher prevalence of imbalance in the right extremity versus the left extremity (Table 4).

SINGLE-LEG DYNAMIC BALANCE

Quality of movement categories were determined by the score on the LSD test – good, moderate, and poor.28 Based on prior research, scores between two and six were utilized as the cut off for increased risk of ACL injury.30 A majority of the sample fell into the “moderate” category. The remainder of the sample was split evenly between the “good” and “poor” quality of movement categories, with four athletes in each. For the LSD test, 11/15 athletes met the high-risk cutoff score with two athletes scoring the maximal score of 6 which signifies altered movement patterns, poor balance, and a higher risk of injury. Furthermore, only 1/15 athletes scored a perfect score of 0 (Table 3).

DISCUSSION

The purpose of this study was to screen female high school soccer and basketball athletes for the presence of modifiable risk factors that predispose them to increased risk of sustaining a non-contact ACL injury that have been identi-
Table 2. Range of Motion.

<table>
<thead>
<tr>
<th>Subject</th>
<th>R Hip IR (deg)</th>
<th>L Hip IR (deg)</th>
<th>R Hip IR+ER (deg)</th>
<th>L Hip IR+ER (deg)</th>
<th>R Q-angle (deg)</th>
<th>L Q-angle (deg)</th>
<th>R Ankle DF (deg)</th>
<th>L Ankle DF (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26*</td>
<td>20*</td>
<td>62*</td>
<td>54*</td>
<td>10</td>
<td>7</td>
<td>35*</td>
<td>27*</td>
</tr>
<tr>
<td>2</td>
<td>29*</td>
<td>28*</td>
<td>64*</td>
<td>68*</td>
<td>5</td>
<td>5</td>
<td>37*</td>
<td>37*</td>
</tr>
<tr>
<td>3</td>
<td>24*</td>
<td>27*</td>
<td>62*</td>
<td>65*</td>
<td>10</td>
<td>10</td>
<td>32*</td>
<td>25*</td>
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<td>4</td>
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<td>25*</td>
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<td>25*</td>
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<td>7</td>
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<td>72*</td>
<td>72*</td>
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<td>28*</td>
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<td>15*</td>
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<td>64*</td>
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<td>15</td>
<td>38*</td>
<td>39*</td>
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<td>9</td>
<td>16*</td>
<td>15*</td>
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<tr>
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<td>95</td>
<td>15</td>
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<td>36*</td>
<td>34*</td>
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<td>11</td>
<td>21*</td>
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<td>69*</td>
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<td>68*</td>
<td>68*</td>
<td>15</td>
<td>12</td>
<td>23*</td>
<td>22*</td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>26.33 (±5.33)</td>
<td>25 (±7.15)</td>
<td>69.33 (±9.68)</td>
<td>69.07 (±13.56)</td>
<td>11.67 (±3.74)</td>
<td>11.67 (±3.68)</td>
<td>30.2 (±7.23)</td>
<td>27.53 (±7.35)</td>
</tr>
</tbody>
</table>

* Met cutoff score
Abbreviations: deg, degrees; DF, dorsiflexion; ER, external rotation; IR, internal rotation; L, left; R, right; SD, standard deviation

Table 3. Measures of Dynamic Motor Control.

<table>
<thead>
<tr>
<th>Subject</th>
<th>LESS (points)</th>
<th>LSDT (points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6*</td>
<td>3*</td>
</tr>
<tr>
<td>2</td>
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<td>0</td>
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<td>3</td>
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<td>4</td>
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<td>10</td>
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<td>11</td>
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<tr>
<td>13</td>
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<tr>
<td>14</td>
<td>5.5*</td>
<td>2*</td>
</tr>
<tr>
<td>15</td>
<td>6.5*</td>
<td>2*</td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>5.17 (±1.03)</td>
<td>2.73 (±1.83)</td>
</tr>
</tbody>
</table>

* Met cutoff score
Abbreviations: LESS, landing error scoring system; LSDT, lateral step-down test; SD, standard deviation

An Anterior Cruciate Ligament (ACL) injury, 11,12,18,19,25,30,32 Several of these studies have focused on screening only one or two of these risk factor components in isolation, 11,12,18,19,25,30,32 There were no studies found in the literature that completed a battery of tests to identify if a female athlete was at increased risk for a non-contact ACL injury, 11,12,18,19,25,30,32 Currently, many authors have focused on identifying ACL injury risk using expensive, high-technology equipment that requires extensive experience, training, and time to use, which would be difficult to implement in a community program. 14,20,26,31 Radiographic measurement is considered more precise than goniometric measurements; however, this method is expensive, exposes subjects to radiation, and is not readily accessible in the environment where most screening programs would be held. 14 Force plates with electromagnetic tracking systems for 3-D analysis is the ideal method to assess jump landing and ground reaction force; however, not all clinics would be able to implement the equipment utilized for analysis due to their expense and spatial requirements. 20 An isokinetic dynamometer is the gold standard to assess strength, but it is expensive and space-consuming. 26 Kinematic motion and quality of movement during the LSD is best visualized using 3-D motion analysis; however, this method requires training and expertise to use properly, is expensive, and is time-consuming, which makes it not ideal for use in a screening program. 31 For the program to be feasible, the chosen screening methods utilized readily accessible equipment and materials that were easy to implement by SPTs. This allowed the program to be conducted in an organized and timely manner.
Biomechanical and neuromuscular components are risk factors that can be identified and modified with appropriate screening and interventions.\textsuperscript{6,33} The screening methods and interventions utilized in this program have been shown to identify and address these types of modifiable risk factors which can be easily applied to clinical practice.\textsuperscript{11,12,18,19,25,30,32} After completion of the screening program, all 15 of the participating athletes demonstrated at least four of the eight modifiable risk factors that were measured. This demonstrates that there are likely several components that each athlete could improve upon, in order to help decrease the risk of an ACL tear.

**LIMITATIONS**

There are several limitations with the present study that need to be considered. First, the small sample size utilized in this study is a limitation. Thus, this is described as a pilot study. Due to the population under study, proximity to the testing facility was needed to participate in data collection. In addition, coordination of transportation presented as a barrier for the parents of the subjects participating in this study. Planning in accordance with sport seasonal demands and personal time away appeared to also challenge participant recruitment. Suggestions for future research would be to plan testing in accordance with practice schedules and at a facility that is easily accessible to the athlete, such as their practice location. A second limitation is the lack of long-term follow-up with at-risk athletes to assess if an ACL injury occurred, and whether that correlated to the findings of the athletes being identified as high-risk for injury or not. It is possible that players who were identified as a higher risk for ACL injuries completed the whole season without an injury or vice versa. Future research would benefit to follow the at-risk athletes through seasonal play to determine which factors in combination predict the outcome of injury and if there is a correlation to leg dominance. This would allow researchers to determine if there is a relationship between the quantity of identified risk factors and the rate of injury risk.

**CONCLUSION**

The screening program utilized was feasible to implement and identified potential risk factors for injury in the cohort of female athletes studied. Prior researchers have analyzed impairments in ROM, landing mechanics, strength, and balance that increase the likelihood of ACL injuries in female athletes; however, no screening programs have investigated these categories together to identify female athletes at elevated risk for an ACL tear. All the studied athletes were found to have at least one factor that could lead to risk of ACL injury. This pilot study provides clinicians with a battery of tests and measures that are quick to perform, inexpensive, and do not require extensive experience.

**DISCLAIMERS**

This study protocol was approved by the Institutional Review Board of Walsh University (#2021007). The authors re-
port no conflicts of interest or financial compensation in the completion of this study.

ACKNOWLEDGEMENTS

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REFERENCES


Isometric Knee Strength is Greater in Individuals Who Score Higher on Psychological Readiness to Return to Sport After Primary Anterior Cruciate Ligament Reconstruction

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Keywords: anterior cruciate ligament reconstruction, psychological readiness, return to sport

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Background
Anterior cruciate ligament (ACL) injury is extremely common among athletes. Rate of second ACL injury due to surgical graft rupture or contralateral limb ACL injury is approximately 15-32%. Psychological readiness to return to sport (RTS) may be an important predictor of successful RTS outcomes. Psychological readiness can be quantified using the ACL Return to Sport after Injury (ACL-RSI) questionnaire, with higher scores demonstrating greater psychological readiness.

Purpose
The purpose of this study was to investigate differences in functional performance and psychological readiness to return to sport among athletes who have undergone primary ACL reconstruction (ACLR).

Study Design
Descriptive cohort study

Methods
Eighteen athletes who had undergone primary ACLR were tested at time of RTS clearance. The cohort was divided into two groups, high score (HS) and low score (LS), based on median ACL-RSI score, and performance on static and dynamic postural stability testing, lower extremity isokinetic and isometric strength testing, and single leg hop testing was compared between the groups using an independent samples t-test.

Results
The median ACL-RSI score was 74.17. The average ACL-RSI score was 83.1±6.2 for the HS group and 61.8±8.0 for the LS group. High scorers on the ACL-RSI performed significantly better on isometric knee flexion as measured via handheld dynamometry (22.61% ±6.01 vs. 12.12% ±4.88, p=0.001) than the low score group.

Conclusion
The findings suggest that increased knee flexion strength may be important for psychological readiness to RTS after primary ACLR. Further research is indicated to

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explore this relationship, however, a continued emphasis on improving hamstring strength may be appropriate during rehabilitation following ACLR to positively impact psychological readiness for RTS.

Level of Evidence

III

INTRODUCTION

Anterior cruciate ligament (ACL) injury is common among athletes.\(^1,2\) Rate of second injury due to surgical graft rupture or contralateral limb injury is approximately 15-32%, with increased risk during the first two years postoperatively.\(^3\) Known factors associated with successful return to sport (RTS) include delay of return until at least nine months postoperatively, symmetric quadriceps strength measured as a ratio of knee extensor torque normalized to body mass, lower levels of pain and knee joint effusion, lower levels of kinesiophobia, and extended preoperative rehabilitation.\(^4\) Successful return to sport is primarily defined as avoidance of second injury, but can also include return to pre-injury activity levels or avoidance of pain with activity. Despite the identification of these predictors, ACL reinjury rates remain high, suggesting that other factors may play an important role in successful RTS. One of these additional factors may be psychological readiness to RTS, which includes fear of reinjury, anxiety, anger, and stress, and lack of confidence to return to sport.\(^1\) Approximately 40-65% of athletes return to their preinjury level of sport after primary ACL injury,\(^1,2,4\) and among athletes who do not return, fear of injury is the most common reason they cite for this decision.\(^5\) Lack of psychological readiness is a major barrier for return to preinjury level of sport after ACL reconstruction (ACLR).\(^5\) Psychological factors, in addition to physical readiness, are important to consider in RTS evaluation.\(^5\)

Several authors have indicated that psychological readiness predicts successful RTS,\(^12,14,19-23\) Psychological readiness to return to sport may be quantified using a questionnaire known as the ACL Return to Sport after Injury (ACLR-SI) scale.\(^24\) Webster et al. developed this 12-item questionnaire in 2008 to assess the psychological impact of returning to sport after ACLR.\(^24\) The scale measures psychological readiness to RTS after an ACL injury in three main categories: emotions, confidence, and risk appraisal, and a higher score suggests greater psychological readiness for return to sport.\(^21,24,25\) The ACL-SI has been shown to be a good indicator of successful RTS.\(^10,11,23\) Sadeqi et al. describes that ACL-SI score improves throughout the rehabilitation process, and that higher ACL-SI score is correlated with an athlete's return to sport.\(^25\) Athletes who return to sport after ACLR have higher ACL-SI scores than athletes who do not return to their sport even after being medically cleared to do so.\(^10,15\) Importantly, young athletes (<20 years of age) who sustain a second ACL injury after RTS had lower psychological readiness scores at 12 months after ACLR and a smaller change in their ACL-SI score from preoperative evaluation to 12 months postoperative evaluation than their counterparts who do not sustain a second injury.\(^21,22\) ACL-SI score indicates psychological readiness for successful RTS, and therefore may be a useful tool in RTS evaluations for athletes.

Although there is strong evidence demonstrating that psychological readiness plays a significant role in successful RTS, the predictors of psychological readiness remain largely unknown. The purpose of this study was to investigate differences in functional performance and psychological readiness to return to sport among athletes who have undergone primary ACLR. Predictors of high ACL-SI scores will be determined based on single leg functional performance in single leg hop for distance, quadriceps strength testing, and single leg static postural stability and Dynamic Postural Stability Index (DPSI). Because athletes with higher ACL-SI scores are shown to have greater success in RTS, it was hypothesized that subjects in this study with higher ACL-SI scores will perform better in functional testing at time of RTS than athletes with lower ACL-SI scores. Findings from this study may guide clinicians when determining how psychological factors contribute to functional performance. Results may also affect both physical and psychological rehabilitation for athletes after ACLR to improve RTS outcomes.

METHODS

STUDY DESIGN AND PARTICIPANTS

This descriptive cohort study utilized individuals who had undergone a primary ACLR at a single academic institution. Subjects were recruited to participate if they were 12 years or older and had undergone primary ACL reconstruction with a contributing author orthopaedic surgeon. A total of 18 participants enrolled in the study voluntarily. All subjects were cleared by their orthopaedic surgeon to return to their previous level of activity prior to participation in the study.

Subjects were included in this study if they participated in a sport at any level prior to their injury, and intended to return back to sport after being cleared to do so. Subjects were excluded if they had a history of any prior major lower extremity injuries, prior lower extremity or back surgery, any medical diagnosis that could affect balance, or any multi-ligamentous injury. Concurrent meniscal injury was not an exclusion criterion. Subject demographics for the cohort are outlined in Table 1. All subjects read and signed an informed consent form prior to participating in the study.

INSTRUMENTATION

Ground reaction forces (GRF) for static and dynamic postural stability testing were collected at 1000 Hz with an AMTI force plate (Advanced Mechanical Technologies, Inc.,
Watertown, MA, model BP600900). Knee isokinetic strength was measured using an isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY), and knee isometric strength was measured using a handheld dynamometer (Lafayette Instrument Company, Lafayette, IN).

PROCEDURES

Participants completed the ACL Return to Sport after Injury (ACL-RSI) 12-item questionnaire at time of RTS clearance, as previously described. Several studies have used the ACL-RSI, and the questionnaire shows high internal consistency (Cronbach alpha = 0.96).14,15,20,21,25,26–28

Subjects also completed the Tegner Activity Scale prior to functional performance testing. The Tegner Activity Scale is a scored assessment from zero to ten that assesses the activity level in daily life and sport or recreation that a participant can comfortably complete.29–31 Participants may only achieve a score of five or greater if they participate in recreational or competitive sports.29 The activity scale has been shown to have high test-retest reliability.29,31 Average Tegner Activity Level for the cohort at time of RTS testing is reported in Table 1.

Static postural stability testing was assessed under eyes open (EO) and eyes closed (EC) conditions. Participants assumed a single-leg stance on their injured leg on the force plate with their hands on their hips and were asked to focus on a marker at eye level approximately ten feet in front of them for a total of ten seconds in EO condition. Subjects assumed the same stance with their eyes closed for EC condition. Subjects completed one practice trial for each condition before three ten second trials were collected for data analysis. Trials were repeated if the subject shifted their standing foot on the force plate or touched down with their opposite foot off of the force plate. This protocol has been previously described and found to have excellent inter-session reliability.32–37 The standard deviation of the GRF were calculated for each trial in the anterior-posterior, medial-lateral, and vertical directions. In addition, an overall composite GRF was calculated for each trial. These values were averaged across the three trials for the eyes open and eyes closed conditions following data reduction.

For dynamic postural stability testing, participants were instructed to jump forward from a two-legged stance over a 30.5 cm hurdle to a force plate that was positioned at a distance of 40% of their height. Subjects were asked to land on their injured leg on the force plate and hold the stance for at least five seconds after landing. Trials were discarded if the subject did not land with one foot entirely on the force plate or if they were unable to hold a single leg stance after landing for at least five seconds. This procedure has been previously described in the literature and has good inter-session reliability.38–39 The dynamic postural stability index (DPSI) for each GRF component was calculated for the anterior-posterior, medial-lateral, and vertical directions, as well as an overall composite index following data reduction.40

Knee strength was first assessed using an isokinetic dynamometer with concentric testing at 60° per second. Subjects were positioned on the isokinetic dynamometer according to manufacturer specifications. Participants were tested for average peak torque for knee flexion and knee extension. Strength was tested on the injured limb. Subjects performed three practice trials of knee flexion and extension at 50% of their maximum strength, followed by three practice trials at maximum strength. Following one minute of rest, participants proceeded with five consecutive repetitions of flexion and extension at maximum strength. This protocol has been previously described in the literature, and has been shown to have good between-group and side-to-side reliability.41,42 Average peak torque for knee flexion and knee extension were calculated and normalized to body mass in kilograms.

A handheld dynamometer was also used to assess isometric knee flexion and extension strength. For knee flexion testing, participants were in the prone position on an exam table with their injured knee in 30–45° of flexion. The subject then accelerated into full flexion strength while the examiner resisted the subject’s flexion using a handheld dynamometer placed on the distal one-third of the calf. For knee extension, participants sat on the edge of the exam table with their legs hanging off in 30–45° of flexion. Using a gait belt strap, the dynamometer was secured on the distal one-third of the tibia of the injured leg, participants accelerated into maximum extension. Each trial with the handheld dynamometer was repeated three times. Handheld dynamometry has been previously described and validated for intra-rater, inter-rater, and inter-device reliability, especially for proximal muscle testing.43–44 Peak force was averaged over the three trials and normalized to body mass in kilograms. One tester performed all of the handheld strength testing. Intra-rater reliability of this tester using the protocol employed in the current study was 0.94 or greater.

Hop distance was assessed for both triple hop and crossover hop. For each hop test, individuals were asked

### Table 1. Participant demographics

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Tegner Activity Level</th>
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<tr>
<td></td>
<td>Mean ±SD</td>
<td>Mean ±SD</td>
<td>Mean ±SD</td>
<td>Mean ±SD</td>
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<tr>
<td>Females (n=8)</td>
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<td>Males (n=10)</td>
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<td>178.97 ±8.02</td>
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<td>7.70 ±1.25</td>
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<tr>
<td>Total (n=18)</td>
<td>20.2 ±6.35</td>
<td>173.15 ±10.06</td>
<td>76.64 ±18.32</td>
<td>7.28 ±1.44</td>
</tr>
</tbody>
</table>
to complete three consecutive hops on the affected foot, jumping as far as possible along a 34" tape measure on the ground. For the triple hop, all three jumps were made on the same side of a tape measure secured to the floor. For the crossover hop, participants alternated on which side of the tape they jumped with each hop in a lateral-medial-lateral pattern. Trials were discarded if participants landed on the tape or if participants did not stick the landing on their final hop. This procedure has been described previously.\textsuperscript{45,46} with intraclass correlation coefficients of 0.82-0.93.\textsuperscript{47} Participants performed a practice trial for each hop test, and data were recorded for two test trials, with the results averaged and normalized to the participant’s height in centimeters.

**DATA REDUCTION**

Custom MATLAB (Mathworks, v7.0.4, Natick, MA) scripts were used for filtering and processing data for static and dynamic postural stability testing. The data was filtered with a low-pass Butterworth filter using a cutoff frequency of 20 Hz. For static postural stability, the GRF from each of the three successful trials were normalized to body mass in kilograms and averaged. The standard deviation of the GRF in the anterior-posterior, medial-lateral, and vertical directions were calculated, as well as a combined measure from all three directions. For dynamic postural stability, a stability index in the anterior-posterior, medial-lateral, and vertical directions was calculated, in addition to a composite score from all three directions. These values were calculated using the first three seconds after initial contact on the force plate, as determined by the time in which vertical GRF was recorded at greater than five percent of the subject’s body mass. The calculations are based on a mean square standardization around a zero point, with lower values for all variables indicating a better score.\textsuperscript{39}

**STATISTICAL ANALYSIS**

The median ACL-RSI score was calculated across the cohort. Participants were divided into two groups of equal participants based on the median score. Groups were designated as "high score" or "low score" ACL-RSI group, relative to the median.

The data for each variable (height, mass, age, ACL-RSI score, time to RTS, static and dynamic postural stability testing, isokinetic knee flexion/extension, isometric knee flexion/extension, triple/crossover hop) was assessed for normality using a Shapiro-Wilk test. Trial data from the participant’s injured limb was assessed. Data from the non-injured limb was not included in this study. An independent samples t-test was used to compare the functional performance, strength, and postural stability testing between the high and low score ACL-RSI groups for each variable, and a Mann-Whitney U test was used if the data did not meet normality criteria. All statistical analysis was performed using IBM SPSS Statistics (IBM SPSS, Version 24). Statistical significance was set a priori at \( p < 0.05 \).

**RESULTS**

The Shapiro-Wilk normality test showed that the data was normally distributed for all variables tested except for age. There was no significant difference in age between the two groups (mean age 18.67±5.17 years and median 17 years in the high-score ACL-RSI group vs. mean age 21.67±7.53 years and median age 18 in the low-score ACL-RSI group, \( p=0.331 \)). The height, body mass, and age demographics between the two groups are presented in Table 2.

The median ACL-RSI score was 74.17. The average ACL-RSI score was 83.1±6.2 for the "high score" group (HS) and 61.8±8.0 for the "low score" group (LS). There was a significant difference in ACL-RSI score between groups (HS= 85.06, LS=61.76, \( p<0.001 \)). The distribution of scores is shown in Figure 1.

The means, standard deviations, and \( p \)-values for the HS and LS group for static and dynamic postural stability tasks are presented in Table 3. None of the comparisons between groups achieved statistical significance. The means, standard deviations, and \( p \)-values between groups for strength testing are presented in Table 4. High scorers on the ACL-RSI had statistically significant greater isometric knee flexion strength normalized to body mass as measured via handheld dynamometry (36.6±11.4 vs. 32.9±11.8, \( p=0.001 \)). There were no other statistically significant findings in isometric and isokinetic strength testing. The means, standard deviations, and \( p \)-values for hop testing between groups are presented in Table 5. There were no statistically significant differences in performance between the HS and LS groups for hop testing.

**DISCUSSION**

The purpose of this study was to evaluate if greater psychological readiness for RTS was associated with better performance on strength, postural stability, and hop testing at time of RTS clearance among athletes who had undergone primary ACL reconstruction. It was hypothesized that participants with greater psychological readiness, as determined by ACL-RSI score, would have greater strength, static and dynamic postural stability, and greater hop distance than participants with lower ACL-RSI scores. The hypothesis was partially supported by the finding that participants with greater psychological readiness for RTS had greater mean isometric knee flexor strength. However, no other statistically significant differences were found between groups in any other performance test measured.

Both psychological readiness to RTS and return of knee flexor strength have been shown to be an important predictor of successful RTS outcomes. Athletes with greater ACL-RSI scores, a marker of psychological readiness, are more likely to return to sport after injury recovery.\textsuperscript{13,22} Further, athletes with lower ACL-RSI scores and a smaller improvement in ACL-RSI score throughout postoperative rehabilitation are more likely to experience a second ACL injury upon returning to sport.\textsuperscript{21} Knee flexor strength deficits after ACLR have been associated with an increased second injury risk.\textsuperscript{48,49}
Table 2. ACL-RSI Group demographics

<table>
<thead>
<tr>
<th></th>
<th>HS Group (n= 9)</th>
<th>LS Group (n = 9)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.43 ± 10.77</td>
<td>169.87 ± 8.66</td>
<td>0.173</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>74.48 ± 11.68</td>
<td>78.80 ± 23.80</td>
<td>0.631</td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>18.67 ± 5.17</td>
<td>21.67 ± 7.33</td>
<td>0.331</td>
</tr>
<tr>
<td>ACL-RSI Score</td>
<td>83.06 ± 6.22</td>
<td>61.76 ± 8.00</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>Mean time to RTS clearance (months)</td>
<td>8.74 ± 1.54</td>
<td>9.50 ± 2.75</td>
<td>0.475</td>
</tr>
</tbody>
</table>

*denotes statistically significant difference
HS= high score ACL-RSI group, LS = low score ACL-RSI group

Previous studies have also identified relationships between strength and functional performance testing with psychological readiness to return to sport. Paterno et al. identified that athletes with greater fear, a component of psychological readiness, were less likely to return to previous levels of activity and were more likely to have isometric knee extensor strength asymmetry and hop testing asymmetry between legs at time of RTS, and were more likely to experience second ACL injuries. Lepley et al. observed that lower levels of presurgical pain and greater knee extensor strength in both the injured and uninjured limbs at time of RTS clearance were associated with greater psychological readiness to return to sport. Burland et al. found that greater isometric and isokinetic extensor strength were associated with higher ACL-RSI scores at three and six months postoperative in adolescent patients. Meierbach et al. and Muller et al. found a positive correlation between ACL-RSI score and triple hop for distance.

The time before recovery of static and postural stability skill after ACLR remains controversial, but has been shown to improve upon training and is often trained in postoperative rehabilitation programs. Balance deficits may persist six months to three years after ACL injury. It is possible that no difference was observed between the high and low score groups on static and postural stability testing because all athletes had been exposed to balance testing throughout rehabilitation and had adequately recovered their balance at time of return to sport testing.

There are several limitations to this study. First, there was a relatively small enrollment size. Generalization of these findings should be done with caution, given the small sample size and small age range of athletes enrolled. Participants volunteered to enroll in the study, so enrollment was limited by their willingness to complete testing leading to selection bias. Additionally, the type of surgical graft used intraoperatively, and postoperative rehabilitation programs were not controlled among participants. Athletes may have exhibited reduced hamstring strength if they received a hamstring autograft, which would be unrelated to psychological readiness. Graft type for each participant was not recorded for this study, therefore we were unable to stratify results based on this finding. Postoperative rehabilitation protocols are not standardized after ACLR, which could contribute to varying levels of familiarity or preparation for the test battery used in this study. However, because participants were tested after RTS clearance by their clinicians, it is assumed that all subjects had demonstrated some level of competency with strength, balance, and functional performance testing prior to enrollment in this study.

CONCLUSION

This study demonstrated an association between greater isometric knee flexor strength and ACL-RSI score, a surrogate of psychological readiness to RTS, partially supporting the hypothesis. We found no association between greater psychological readiness to RTS and knee extensor strength, static or dynamic postural stability, or hop testing among the cohort. Findings from this study indicate that improving hamstring strength may contribute to greater psychological readiness to return to sport, both of which may help reduce second ACL injury rates. Given that psychological readiness has been shown to be related to successful RTS outcomes and lower second injury rates, future research...
Table 3. Static and dynamic postural stability testing

<table>
<thead>
<tr>
<th></th>
<th>HS Group (n= 9)</th>
<th>LS Group (n = 9)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Static Balance GRF - AP, EO</td>
<td>2.68 ± 0.73</td>
<td>2.71 ± 1.10</td>
<td>0.947</td>
</tr>
<tr>
<td>Static Balance GRF - ML, EO</td>
<td>3.53 ± 1.29</td>
<td>3.53 ± 1.73</td>
<td>0.993</td>
</tr>
<tr>
<td>Static Balance GRF - V, EO</td>
<td>5.64 ± 1.68</td>
<td>5.17 ± 2.34</td>
<td>0.630</td>
</tr>
<tr>
<td>Static Balance GRF - Combined, EO</td>
<td>7.20 ± 2.15</td>
<td>6.85 ± 3.05</td>
<td>0.780</td>
</tr>
<tr>
<td>Static Balance GRF - AP, EC</td>
<td>5.33 ± 1.53</td>
<td>6.29 ± 4.02</td>
<td>0.510</td>
</tr>
<tr>
<td>Static Balance GRF - ML, EC</td>
<td>9.09 ± 4.39</td>
<td>10.80 ± 7.02</td>
<td>0.545</td>
</tr>
<tr>
<td>Static Balance GRF - V, EC</td>
<td>12.48 ± 5.09</td>
<td>12.85 ± 7.02</td>
<td>0.898</td>
</tr>
<tr>
<td>Static Balance GRF - Combined, EC</td>
<td>16.42 ± 6.65</td>
<td>17.99 ± 10.59</td>
<td>0.711</td>
</tr>
<tr>
<td>DPSI</td>
<td>0.35 ± 0.05</td>
<td>0.36 ± 0.04</td>
<td>0.479</td>
</tr>
<tr>
<td>APSI</td>
<td>0.14 ± 0.01</td>
<td>0.14 ± 0.01</td>
<td>0.303</td>
</tr>
<tr>
<td>MLSI</td>
<td>0.03 ± 0.00</td>
<td>0.03 ± 0.01</td>
<td>0.950</td>
</tr>
<tr>
<td>VSI</td>
<td>0.32 ± 0.05</td>
<td>0.33 ± 0.04</td>
<td>0.505</td>
</tr>
</tbody>
</table>

GRF= ground reaction forces, EO= eyes open, EC = eyes closed, AP= anterior-posterior, ML= medial-lateral, V= vertical, HS= high score ACL-RSI group, LS = low score ACL-RSI group

Table 4. Strength testing

<table>
<thead>
<tr>
<th></th>
<th>HS Group (n= 9)</th>
<th>LS Group (n = 9)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Isokinetic Knee flexion avg peak torque/ BM *100</td>
<td>124.98% ± 25.87</td>
<td>102.03% ± 46.49</td>
<td>0.214</td>
</tr>
<tr>
<td>Isokinetic Knee extension avg peak torque / BM * 100</td>
<td>189.06% ± 45.63</td>
<td>192.68% ± 67.99</td>
<td>0.896</td>
</tr>
<tr>
<td>Handheld dynamometry knee flexion avg peak force/ BM * 100</td>
<td>22.61% ± 6.01</td>
<td>12.12% ± 4.88</td>
<td>0.001*</td>
</tr>
<tr>
<td>Handheld dynamometry knee extension avg peak force/ BM *100</td>
<td>36.55% ± 11.37</td>
<td>32.90% ± 11.82</td>
<td>0.528</td>
</tr>
</tbody>
</table>

*denotes statistical significance
HS= high score ACL-RSI group, LS = low score ACL-RSI group, BM = body mass (kg)

Table 5. Hop testing

<table>
<thead>
<tr>
<th></th>
<th>HS Group (n= 9)</th>
<th>LS Group (n = 9)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Triple hop distance / height</td>
<td>265.19 ± 55.65</td>
<td>209.74 ± 65.66</td>
<td>0.071</td>
</tr>
<tr>
<td>Crossover hop distance / height</td>
<td>238.94 ± 54.17</td>
<td>187.58 ± 73.91</td>
<td>0.112</td>
</tr>
</tbody>
</table>

HS= high score ACL-RSI group, LS = low score ACL-RSI group

should explore ways to train and optimize psychological readiness in addition to functional strength prior to an athlete’s return to sport.

IRB PROTOCOL

Pro00088053 DUHS IRB
Submitted: August 11, 2021 CST, Accepted: August 16, 2022 CST

CONFLICTS OF INTEREST AND FINANCIAL DISCLOSURES

None

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REFERENCES


Psychological Patient-reported Outcomes Cannot Predict a Second Anterior Cruciate Ligament Injury in Patients who Return to Sports after an Anterior Cruciate Ligament Reconstruction

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Keywords: anterior cruciate ligament, knee self efficacy scale, patient reported outcomes, psychological outcomes, return to sport, return to sport after injury scale

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Background

Psychological patient-reported outcomes (PROs) are recommended for use in test batteries to aid in decision-making, regarding whether patients are well prepared to return to sports (RTS) after anterior cruciate ligament (ACL) reconstruction. However, the values that should be regarded as "pass" or "fail" are still unclear.

Purpose

This study aimed to identify cut-off values for three commonly used psychological PROs that could differentiate patients who suffer a second ACL injury from patients who do not within two years of RTS in patients after ACL reconstruction with respect to recovery of symmetrical quadriceps strength.

Study design

Diagnostic/prognostic study

Methods

Demographic data, isokinetic strength test data for quadriceps, as well as results for the ACL-Return to Sport after Injury scale (ACL-RSI), Knee Injury and Osteoarthritis Outcome Score (KOOS) Quality of Life, and Function in Sport and Recreation sub-scales, and the 18-item version of the Knee Self-Efficacy Scale (K-SES18) were extracted from a registry. Receiver operating characteristic (ROC) curves were calculated for each PRO. Accuracy of the cut-offs was presented with two summary measures for the ROC: the area under the curve (AUC) and Youden index.

Results

In total, 641 (355 men, 61%) patients (24.8 [SD 7.6] year old at ACL reconstruction) were included. The cut-off values were not able to differentiate patients who suffered a second ACL injury up to 24 months after RTS and ACL reconstruction from patients who did not. Additionally, achieving symmetrical quadriceps strength did not improve the cut-off psychometric properties.

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Conclusion
Since cut-off values could not differentiate between patients who suffered a second ACL injury and those who did not, clinicians should not rely only on cut-off values or a single PRO of those analyzed in this study when making decisions on which patients are at risk of experiencing a second ACL injury when returning to sports after ACL reconstruction.

Level of Evidence
Level 3

INTRODUCTION
Anterior cruciate ligament (ACL) injury is most commonly treated with rehabilitation, and about 50% of patients undergo surgical reconstruction of the ruptured ligament. To sustain a second ACL injury after ACL reconstruction can be devastating; and this further increases the risk for long-term consequences, such as osteoarthritis and lower levels of physical activity and perceived quality of life. A common goal for patients treated with rehabilitation and ACL reconstruction is to return to sport (RTS). As participating in sports is associated with a risk of sustaining a second ACL injury, a primary concern is to evaluate the patients readiness for RTS, i.e. returning to sports with minimal risk for suffering a second ACL injury.

Responses to psychological patient-reported outcomes (PROs) can differ between patients who suffer a second ACL injury and those who do not, as patients who suffer a second ACL injury have reported greater scores, that is, better responses, on validated PROs. Collected evidence, including the results from systematic reviews on psychological outcomes after ACL reconstruction and clinical practice guidelines, as well as patients' experiences, suggest that psychological PROs should be used in test batteries to help identify whether patients are well prepared for RTS after ACL reconstruction.

An issue related to the use of PROs in RTS test batteries is, which cut-off values best identify whether patients "pass" (patients can be cleared to RTS) or "fail" (patients should be advised against RTS)? Different cut-offs for different PROs and outcomes have been proposed. Notably, some cut-offs commonly used in the decision-making if the patient can RTS have not been anchored against a second ACL injury, but are instead based on responses from PROs that were collected several months prior to patients suffering a second ACL injury. It is important to acknowledge that the reasons for a second ACL injury are multifactorial and include genetic, physical, psychological, trauma, and surgical factors. Recovery of symmetrical quadriceps strength has been proposed as a possible protective factor that can reduce the risk of a second ACL injury in high-level athletes with RTS. However, the results are inconclusive.

There is a need to better understand which cut-offs for PROs best predict a second ACL injury in patients treated with ACL reconstruction, especially regarding protective factors for a second ACL injury, such as the recovery of symmetrical quadriceps strength. This study aimed to identify cut-off values for three commonly used psychological PROs that could differentiate patients who suffer a second ACL injury from those who do not within two years of RTS after ACL reconstruction with respect to recovery of symmetrical quadriceps strength.

METHODS
Following the guidelines from the Enhancing the Quality and Transparency of Health Research (EQUATOR) network, the Standards for Reporting Diagnostic Accuracy (STARD) statement was used as a checklist to report this study.

Data for the present study were prospectively collected from a rehabilitation outcome registry, the Project ACL. The registry was established in 2014, which aims to improve the care of patients with ACL injuries. Data in the Project ACL consists of results from muscle function tests and PROs collected prospectively before the surgery (in case of ACL reconstruction), at 10 weeks, 4, 8, 12, 18, and 24 months, and every five years with ACL injury/reconstruction as a baseline. Prior to participation in the Project ACL, written consent was collected. Ethical approval was obtained from the Swedish Ethical Review Authority (registration number: 2020-02501).

INCLUSION AND EXCLUSION CRITERIA
All consecutive patients registered in the Project ACL with one ACL injury treated with reconstruction with or without sustaining a subsequent second ACL injury within two years from RTS (Tegner Activity Scale (Tegner) >6) were eligible for inclusion. The patients included in this study were followed up for two years after RTS. Patients were excluded if one of the following criteria were fulfilled: age <16 or >50 years; not participating in knee-strenuous sports prior to index ACL injury, i.e. reporting a Tegner Activity Scale of <6; sustaining a second ACL injury before surgical reconstruction; or not participating in any of the follow-ups of project ACLs. Second ACL injuries are reported by patients themselves, responsible physical therapists, or the test leader at follow-up in Project ACL.

PATIENT REPORTED OUTCOMES
The PROs used in this study were the ACL-Return to Surgery after Injury scale (ACL-RSI), Knee Injury and Osteoarthritis Outcome Score subscale Quality of Life (KOOS QoL), and Function in sport and recreation (KOOS Sports), the 18-item version of the Knee Self-Efficacy Scale (K-SES) and Tegner Activity Scale. The ACL-RSI aims to measure patients' emotions, confidence, and risk appraisal of RTS after an ACL injury. Herein,
the validated 12-item short version was used. Each item was graded from 0 to 10, where 10 is the highest response, representing the best possible psychological response to RTS (highest confidence and emotion, and lowest risk appraisal). The final score is calculated by summing the total score of all items (highest score 120), and then normalizing the score to a 0-100 scale as proposed in the original paper.27

The K-SES18 aims to evaluate knee-related self-efficacy,29 that is, the belief in one's ability to perform a physical task, such as running or jumping. The K-SES18 comprises 18 items divided into two subscales: present (14 items) and future (four items) knee self-efficacies. Each item was graded from 0 to 10, with 10 being the most positive response, representing the greatest belief in carrying out a given physical task. The results from each item were added and divided by the number of items to generate a mean value for the subscales.

The KOOS QoL and KOOS Sports were used in the assessment of patients with ACL injury.28 They comprise four (QoL) and five (Sports) items, respectively. The KOOS QoL assess how often patients are reminded of their knee problems, whether patients can trust their knee function, have to make life changes due to knee function, and whether patients experience problems related to the knee. The KOOS Sports comprises five items assessing a patient's perceived difficulty in performing different tasks, such as running and jumping during the last week. Each item is rated from 0 to 4 on a 5-point Likert scale, and a normalized score from 0 to 100 is calculated for each subscale, where 0 indicates the most severe symptoms, and 100 indicates no symptoms.

The Tegner Activity Scale (Tegner)26 aims to measure strenuous knee activity. Patients grade their activity based on work and sports activities on a scale from 1 to 10, where one represents disability because of knee problems and 10 represents, for example, national or international level soccer. From level 6 on the Tegner, only sports activities are registered, and therefore when patients rate Tegner 96, it is assumable patients are active in a knee strenuous sport.

STRENGTH TESTING

Strength tests for unilateral concentric knee extension and flexion were performed according to a standardized protocol,30 with an isokinetic dynamometer [Biodex System 4 (Biodex Medical Systems, Shirley, New York, USA)]. The testing procedure started with a standardized warm-up of 10 minutes on a stationary bike and sub-maximum trials on each test. The injured leg was tested first, followed by the uninjured leg. Isokinetic testing was performed at an angular velocity of 90°/s with the patients in a seated position. Three maximum repetitions with approximately 40 s of rest between each repetition were performed, and the greatest peak torque was recorded in the Project ACL database. For this study, the results from the unilateral knee extension test were extracted for analysis.

STUDY EXECUTION

In this study, demographic data, results from PROs, and strength tests for the quadriceps were extracted for analysis from the Project ACL in November 2021.

Time frame for returning to knee-strenuous sports typically varies between 6-13 months31 after primary ACL reconstruction. Results of the PROs and strength tests from the follow-up closest in time to RTS (Tegner Activity Scale, level ≥6) were selected for the included patients as the "index test."

Primary outcomes of this study were the cut-off values with sensitivity and specificity for predicting a second ACL injury for each of the included PROs. Therefore, patients who did not go on to suffer a second ACL injury were treated as a reference, and patients who suffered a second ACL injury were treated as having the outcome of interest. Clinical reference standard was not applicable, as the analysis aimed to predict the outcome of interest. In order to account for the recovery of symmetrical quadriceps strength as a protective factor,21,32 sensitivity analyses were performed with regard to patients who had and had not recovered >90% of their quadriceps strength in the injured limb compared to the uninjured limb.33 Symmetrical quadriceps strength was presented with the limb symmetry index (LSI), where result from the injured limb was divided with result from the uninjured limb and multiplied by 100.

STATISTICS

Receiver operating characteristics (ROC) were calculated for each PRO at available follow-ups within two years of RTS (Tegner ≥6). The ROC is a graphical method of displaying the discriminatory accuracy of a marker (in this case, responses to PROs) for separating two populations, or distinguishing between patients affected by an outcome, that is, suffering a second ACL injury within two years after RTS (return to Tegner ≥6), and individuals not affected by the outcome of interest, that is, patients who did not suffer a second ACL injury within two years after RTS. A patient was assessed as "positive" if the tested PRO value was greater than a given threshold value; otherwise, the patient was assessed as negative.34 The accuracy of any given threshold value was measured by the probability of a true positive (sensitivity) and true negative (specificity), and presented with two summary measures for ROC: the area under the curve (AUC) and Youden index. The area under the curve (AUC) is a measure of the ability of a classifier to distinguish between outcomes and is used as a summary of the ROC curve. The higher the AUC, the better the performance of the model in distinguishing between positive and negative outcomes. When AUC is comprised between 0.5 and 1, there is a chance that the classifier can be able to distinguish the positive class values from the negative class values, depending on the AUC value, according to the following rule of thumb: 0.5 = no discrimination, with the same value of a coin flip; 0.5-0.7 = poor discrimination, not much better than a coin flip; 0.7-0.8 = acceptable discrimination; 0.8-0.9 = excellent discrimination; and >.9 = outstanding discrimination.35 Therefore, when interpret-
Patients available for inclusion from Project ACL
n = 2671

Included patients
n = 641

Patients excluded due to:
- Age under 16 or over 50 years n = 339
- Pre-injury Tegner activity scale <6 n = 867
- Had not RTS after ACL reconstruction n = 553
- Did not have 2 years follow-up after RTS n = 271

Figure 1. Flowchart on inclusion and exclusion.
ACL = Anterior Cruciate Ligament; RTS = Return to Sport (return to Tegner Activity level ≥6); n = number

ing the AUC; values between 0.7 to 0.8 were considered to reflect acceptable accuracy.\(^{36}\) The Youden Index is a frequently used summary measure of the ROC and it measures the effectiveness of a diagnostic marker and enables the selection of an optimal threshold value (cut-off point) for the marker.\(^{34}\) The Youden index value ranges from 0 to 1,\(^{37}\) where 0 means that a diagnostic test gives the same proportion of positive results for groups with and without the disease, i.e. the test is useless, while a value of 1 indicates that there are no false positives or false negatives, i.e. the test is perfect.

Statistical analyses were performed using Statistical Analysis System (SAS) software version 9 (SAS Institute Inc., Cary, North Carolina, USA). Mean values with standard deviations (SD) or medians with minimum and maximum are presented for the demographic data. Significance level was set at 0.05.

RESULTS

In total, 641 patients (355 men, 61%) were included in the present study. Figure 1 shows the inclusion and exclusion process. Table 1 presents the demographic characteristics of the patients.

Figure 2 presents the frequency of a second ACL injury stratified by months from return to knee-demanding activity (Tegner ≥6).

Table 2 presents the Youden index with specificity and sensitivity, as well as the model AUC for all assessed PROs.

The cut-offs that best differentiated patients who suffered a second ACL injury after ACL reconstruction from patients who had not were: ≥71.7 for the ACL-SSI, <56 for the KOOS QoL, ≥96.0 for the KOOS Sports, ≥9.4 for the K-SES\(_{18}\) present and ≥7.0 for the K-SES\(_{18}\) future. The AUC and Youden index for each cut-off were below acceptable values, indicating the inability of the cut-offs to properly differentiate between patients who suffered a second ACL injury after ACL reconstruction and those who did not. Table 3 presents the number of patients who suffered a second ACL injury in relation to the achievement of the cut-off values for the different PROs.

**EFFECT OF RECOVERY OF SYMMETRICAL QUADRICEPS STRENGTH**

Table 4 presents the cut-off analysis stratified according to patients who had and had not achieved an LSI of ≥90% in the quadriceps strength test at the time of RTS.

**INTERPRETATION OF RESULTS**

Stratifying patients based on achieved symmetrical quadriceps strength (>90% LSI) or not at the time of RTS did not lead to cut-off values with better psychometric properties, i.e., the Youden index or AUC compared with the cut-offs determined for the entire cohort. In the current results, the best Youden index was 0.24, and the best AUC was 0.613, which is well below acceptable levels.\(^{36,37}\) Therefore, the calculated cut-offs appear unable to separate the two outcomes, with or without a second ACL injury.

Table 5 presents the number of patients who suffered a second ACL injury in relation to the achievement of the cut-offs for the different PROs in patients who achieved symmetrical quadriceps strength at the time of RTS.

**DISCUSSION**

The main finding from this registry study was that the determined cut-off values for different PROs were not able to differentiate patients who suffered a second ACL injury up to 24 months after RTS following ACL reconstruction from patients who did not. Additionally, achieving symmetrical quadriceps strength, i.e., >90% LSI did not improve the cut-offs’ psychometric properties. Regardless of recovering symmetrical quadriceps strength, patients with either a higher or lower knee perceived quality of life, knee-related self-efficacy, confidence, emotions, and risk appraisal appear as likely to suffer a second ACL injury. Therefore, it can be assumed that passing the calculated cut-off for PROs...
Table 1. Demographic data, mean values, standard deviations (SD), count (n) and proportions (%).

<table>
<thead>
<tr>
<th></th>
<th>All patients; n=641</th>
<th>Men; n=355</th>
<th>Women; n=286</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at reconstruction, years</td>
<td>24.8 (7.6)</td>
<td>25.8 (7.4)</td>
<td>23.5 (7.6)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>175.7 (9.3)</td>
<td>181.7 (6.4)</td>
<td>168.2 (6.5)</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>73.5 (12.7)</td>
<td>80.9 (10.2)</td>
<td>64.2 (8.9)</td>
</tr>
<tr>
<td>BMI</td>
<td>23.7 (2.8)</td>
<td>24.5 (2.6)</td>
<td>22.7 (2.7)</td>
</tr>
<tr>
<td>Time to RTS, months</td>
<td>11.8 (15.1)</td>
<td>10.3 (13.8)</td>
<td>13.6 (16.4)</td>
</tr>
<tr>
<td>Ipsilateral second ACL injury</td>
<td>9 (29.0%)</td>
<td>12 (41.4%)</td>
<td>7 (24.2%)</td>
</tr>
<tr>
<td>Hamstring graft, n (%)</td>
<td>465 (72.5%)</td>
<td>260 (73.2%)</td>
<td>205 (71.7%)</td>
</tr>
<tr>
<td>Patellar graft, n (%)</td>
<td>77 (12.0%)</td>
<td>43 (12.1%)</td>
<td>34 (11.9%)</td>
</tr>
<tr>
<td>Other graft, n (%)</td>
<td>6 (0.9%)</td>
<td>2 (0.6%)</td>
<td>4 (1.4%)</td>
</tr>
<tr>
<td>Unknown n (%)</td>
<td>93 (14.5%)</td>
<td>50 (14.1%)</td>
<td>43 (15.0%)</td>
</tr>
<tr>
<td>Graft choice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return to pre-injury Tegner</td>
<td>442 (69.0%)</td>
<td>248 (69.9%)</td>
<td>194 (67.8%)</td>
</tr>
<tr>
<td>Return to pre-injury Tegner</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Months from index reconstruction</td>
<td>4 (24.4%)</td>
<td>79 (31.8%)</td>
<td>29 (15%)</td>
</tr>
<tr>
<td>5-8</td>
<td>75 (17%)</td>
<td>45 (18.1%)</td>
<td>30 (15.5%)</td>
</tr>
<tr>
<td>9-12</td>
<td>128 (29%)</td>
<td>61 (24.6%)</td>
<td>67 (34.5%)</td>
</tr>
<tr>
<td>12-24</td>
<td>70 (15.8%)</td>
<td>35 (14.1%)</td>
<td>35 (18.0%)</td>
</tr>
<tr>
<td>&gt;24</td>
<td>61 (13.8%)</td>
<td>28 (11.3%)</td>
<td>33 (17%)</td>
</tr>
<tr>
<td>Second ACL injury within 24 months from RTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes n (%)</td>
<td>64 (10.0%)</td>
<td>31 (8.7%)</td>
<td>33 (11.5%)</td>
</tr>
<tr>
<td>Ipsilateral second ACL injury</td>
<td>43 (67.2%)</td>
<td>22 (71.0%)</td>
<td>21 (63.6%)</td>
</tr>
<tr>
<td>Contralateral second ACL Injury n (%)</td>
<td>21 (32.8%)</td>
<td>9 (29.0%)</td>
<td>12 (36.4%)</td>
</tr>
</tbody>
</table>

ACL = Anterior Cruciate Ligament; BMI = Body Mass Index; cm = centimeters; kg = kilograms; n = number; RTS = Return to Sport; Tegner = Tegner Activity Scale

used in the present study is not sufficient for safe RTS. Caution must thus be taken if patients are cleared to RTS based on the cut-off values used in the present study, regardless, if they achieve >90% LSI in quadriceps strength or not.

The used cut-off values for PROs in this study could not generate an acceptable AUC value (0.7-0.8), indicating that the cut-off values are no better than 'flipping a coin' when used to assess the risk of suffering a second ACL injury. The poor discriminative ability of the cut-offs can be partly explained by the specificity and sensitivity values. The sensitivity ranged between 0.19-0.59 for all the cut-offs except for the K-SES, future (0.78). Using the ACL-RSI as an example, a sensitivity of 0.50 means that half of the patients who suffered a second ACL injury had a score above 71.7. Further, when a patient scores above 71.7 on the ACL-RSI, there is approximately a 50% chance to correctly guess if the patient will go on to suffer a second ACL injury (AUC = 0.553); therefore, the psychometric value for the cut-off is very low (Youden index = 0.13). Since the cut-offs that best differentiated patients who suffered a second ACL injury from patients who did not have low AUC values, there is a possibility that the PROs used in this study are not suitable for identifying patients who are at increased risk of a second ACL injury at the time of RTS. One issue related to the inability of PROs to identify patients who will continue to suffer a second ACL injury can be related to the development of the PROs used in this study. The ACL-RSI was developed to assess confidence, emotion, and risk appraisal of RTS after ACL injury, which are three different psychological domains (constructs). However, the ACL-RSI is summarized into a single score, ranging between 0-100; this may be questionable because the scale comprises three domains, which can lead to limitations as it induces indirectness towards the outcome when interpreting the PRO as a single score. When assessing the KOOS, using a stringent psychometric method, i.e. the Rasch analysis, criteria for one-dimensionality are respected only in two out of the five subscales,
Psychological Patient-reported Outcomes Cannot Predict a Second Anterior Cruciate Ligament Injury in Patients who Return... (International Journal of Sports Physical Therapy)

Figure 2. Frequency of a second ACL injury for every month after RTS.

ACL = Anterior Cruciate Ligament; RTS = Return to Sport (defined as return to Tegner Activity level ≥6); n = number

Table 2. Cut-off values, Youden index, and specificity and sensitivity for the included PROs in the analysis.

<table>
<thead>
<tr>
<th>PROs</th>
<th>n</th>
<th>Cut-off</th>
<th>Youden Index</th>
<th>1 - Specificity</th>
<th>Sensitivity</th>
<th>Model AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL-RSI</td>
<td>382</td>
<td>71.7</td>
<td>0.13</td>
<td>0.37</td>
<td>0.50</td>
<td>0.553</td>
</tr>
<tr>
<td>KOOS QoL</td>
<td>627</td>
<td>56.0</td>
<td>0.12</td>
<td>0.47</td>
<td>0.59</td>
<td>0.531</td>
</tr>
<tr>
<td>KOOS Sports</td>
<td>627</td>
<td>96.0</td>
<td>0.12</td>
<td>0.07</td>
<td>0.19</td>
<td>0.557</td>
</tr>
<tr>
<td>K-SES_{18} present</td>
<td>630</td>
<td>9.4</td>
<td>0.09</td>
<td>0.26</td>
<td>0.34</td>
<td>0.520</td>
</tr>
<tr>
<td>K-SES_{18} future</td>
<td>630</td>
<td>7.0</td>
<td>0.08</td>
<td>0.70</td>
<td>0.78</td>
<td>0.511</td>
</tr>
</tbody>
</table>

PROs = Patient Reported Outcomes; n = number i.e., patients responding (please note ACL-RSI is not administered at all follow-ups); ACL-RSI = Anterior Cruciate Ligament Return to Sport after Injury Scale; KOOS = Knee injury and Osteoarthritis Outcome Score; QoL = subscale Quality of Life; K-SES = Knee Self-Efficacy Scale; AUC = Area Under the Curve

Table 3. Proportion and number of patients above or below cut-offs who suffered a second ACL injury.

<table>
<thead>
<tr>
<th>PROs</th>
<th>Cut off</th>
<th>Second ACL injury, % (n)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL RSI</td>
<td>≥71.7</td>
<td>14% (19)</td>
<td>8.4% 20.5%</td>
</tr>
<tr>
<td></td>
<td>&lt;71.7</td>
<td>9% (21)</td>
<td>5.4% 12.9%</td>
</tr>
<tr>
<td>KOOS QoL</td>
<td>≥56</td>
<td>10% (40)</td>
<td>7.2% 13.2%</td>
</tr>
<tr>
<td></td>
<td>&lt;56</td>
<td>11% (24)</td>
<td>7.0% 15.6%</td>
</tr>
<tr>
<td>KOOS Sports</td>
<td>≥96</td>
<td>23% (12)</td>
<td>12.5% 36.8%</td>
</tr>
<tr>
<td></td>
<td>&lt;96</td>
<td>9% (52)</td>
<td>6.8% 11.7%</td>
</tr>
<tr>
<td>K-SES present</td>
<td>≥9.4</td>
<td>23% (12)</td>
<td>12.5% 36.8%</td>
</tr>
<tr>
<td></td>
<td>&lt;9.4</td>
<td>9% (52)</td>
<td>6.8% 11.7%</td>
</tr>
<tr>
<td>K-SES future</td>
<td>≥7</td>
<td>23% (12)</td>
<td>12.5% 36.8%</td>
</tr>
<tr>
<td></td>
<td>&lt;7</td>
<td>9% (52)</td>
<td>6.8% 11.7%</td>
</tr>
</tbody>
</table>

PROs = Patient Reported Outcomes; ACL = Anterior Cruciate Ligament; n = number i.e., patients responding; CI = Confidence Interval; ACL-RSI = Anterior Cruciate Ligament Return to Sport after Injury Scale; KOOS = Knee injury and Osteoarthritis Outcome Score; QoL = subscale Quality of Life; K-SES = Knee Self-Efficacy Scale
Table 4. Cut-off values, Youden index, and specificity and sensitivity for the included PROs in the analysis, stratified by whether patients achieved symmetrical quadriceps strength or not.

<table>
<thead>
<tr>
<th>Patients with LSI of ≥90% (n=308)</th>
<th>n</th>
<th>Cut-off</th>
<th>Youden Index</th>
<th>1 - Specificity</th>
<th>Sensitivity</th>
<th>Model AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL-RSI</td>
<td>220</td>
<td>71.7</td>
<td>0.22</td>
<td>0.35</td>
<td>0.57</td>
<td>0.591</td>
</tr>
<tr>
<td>KOOS QoL</td>
<td>307</td>
<td>56.0</td>
<td>0.24</td>
<td>0.35</td>
<td>0.59</td>
<td>0.580</td>
</tr>
<tr>
<td>KOOS Sports</td>
<td>307</td>
<td>96.0</td>
<td>0.18</td>
<td>0.09</td>
<td>0.27</td>
<td>0.600</td>
</tr>
<tr>
<td>K-SES&lt;sub&gt;18&lt;/sub&gt; present</td>
<td>308</td>
<td>9.4</td>
<td>0.17</td>
<td>0.34</td>
<td>0.51</td>
<td>0.569</td>
</tr>
<tr>
<td>K-SES&lt;sub&gt;18&lt;/sub&gt; future</td>
<td>308</td>
<td>8.3</td>
<td>0.05</td>
<td>0.62</td>
<td>0.68</td>
<td>0.495</td>
</tr>
</tbody>
</table>

| Patients with LSI of ≤90% (n=181) | ACL-RSI | 87 | 46.7 | 0.23 | 0.77 | 1.00 | 0.561 |
| KOOS QoL                          | 179 | 38.0 | 0.13 | 0.81 | 0.94 | 0.537 |
| KOOS Sports                       | 179 | 55.0 | 0.24 | 0.61 | 0.84 | 0.613 |
| K-SES<sub>18</sub> present        | 180 | 6.1  | 0.21 | 0.74 | 0.95 | 0.537 |
| K-SES<sub>18</sub> future         | 180 | 8.0  | 0.22 | 0.57 | 0.79 | 0.523 |

PROs = Patient Reported Outcomes; n = number, i.e., patients responding (please note that ACL-RSI is not administered at all follow-ups); LSI = Limb Symmetry Index; ACL-RSI = Anterior Cruciate Ligament Return to Sport after Injury Scale; KOOS = Knee injury and Osteoarthritis Outcome Score; QoL = subscale Quality of Life; K-SES = Knee Self-Efficacy Scale; AUC = Area Under the Curve.

Table 5. Proportion and number of patients above or below the determined cut-offs who suffer a second ACL injury were stratified, depending on whether the patients achieved symmetrical quadriceps strength or not at the time of RTS.

<table>
<thead>
<tr>
<th>PROs</th>
<th>Cut-off</th>
<th>Second ACL injury, % (n)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL-RSI</td>
<td>≥71.7</td>
<td>18.7% (15)</td>
<td>10.9% – 29.0%</td>
</tr>
<tr>
<td></td>
<td>&lt;71.7</td>
<td>9.3% (13)</td>
<td>3.3% – 15.2%</td>
</tr>
<tr>
<td>KOOS QoL</td>
<td>≥56</td>
<td>11.6% (27)</td>
<td>5.8% – 17.4%</td>
</tr>
<tr>
<td></td>
<td>&lt;56</td>
<td>13.3% (10)</td>
<td>6.4% – 20.2%</td>
</tr>
<tr>
<td>KOOS Sports</td>
<td>≥96</td>
<td>29.4% (10)</td>
<td>15.1% – 43.7%</td>
</tr>
<tr>
<td></td>
<td>&lt;96</td>
<td>9.9% (27)</td>
<td>5.3% – 14.4%</td>
</tr>
<tr>
<td>K-SES&lt;sub&gt;18&lt;/sub&gt; present</td>
<td>≥9.4</td>
<td>11.6% (9)</td>
<td>5.7% – 17.5%</td>
</tr>
<tr>
<td></td>
<td>&lt;9.4</td>
<td>12.0% (10)</td>
<td>5.6% – 18.5%</td>
</tr>
<tr>
<td>K-SES&lt;sub&gt;18&lt;/sub&gt; future</td>
<td>≥8.3</td>
<td>29.4% (10)</td>
<td>15.1% – 43.7%</td>
</tr>
<tr>
<td></td>
<td>&lt;8.3</td>
<td>9.9% (27)</td>
<td>5.3% – 14.4%</td>
</tr>
</tbody>
</table>

PROs = Patient Reported Outcomes; ACL = Anterior Cruciate Ligament; n = number, i.e., patients responding; CI = Confidence Interval; ACL-RSI = Anterior Cruciate Ligament Return to Sport after Injury Scale; KOOS = Knee injury and Osteoarthritis Outcome Score; QoL = subscale Quality of Life; K-SES = Knee Self-Efficacy Scale; RTS = Return To Sport.
i.e. KOOS Sports and KOOS Quality of life. Furthermore, the KOOS’s development quality has been rated as “inadequate,” and the KOOS’s psychometric properties with regard to patients with an ACL injury have been reported to be “poor,” “insufficient,” and “inconsistent,” but the authors opinions are based on that studies evaluating the psychometric properties are lacking. The inconsistency reported in the psychometric properties of the KOOS with regard to patients with an ACL injury can be due to issues during scale development, since no patients who suffered an ACL injury participated in the development and were asked whether the items were relevant.

As for the K-SES, a recent publication reported that it has acceptable reliability and validity for measuring self-efficacy in patients with ACL injury. However, no Rasch analysis has yet been performed on the K-SES, and good psychometric values can be obtained by correlating the K-SES with other scales of debatable psychometric properties, such as the KOOS, leading to possible misinterpretation of results. Finally, the inability of PROs to identify patients who would suffer a second ACL injury is likely related to the fact that patients with a second ACL injury were not taken into account when developing PROs.

LIMITATIONS

One limitation of this study was the relatively small number of patients in the second ACL injury group (n=64), which could have influenced the statistical power. A post-hoc power calculation was performed, which showed that 33 patients in each group were needed to detect an AUC of 0.7 with a 90% power and an alpha of 0.05. Due to the heterogeneity in the population of patients who suffered an ACL injury, 33 patients per group might still not be sufficient for the statistical power; therefore, the results should be appreciated with caution. Another limitation of the present study could be its conceptual character. A second ACL injury is multifactorial, and both high and low values on PROs can be risk factors for a second ACL injury. Assuming that both high and low knee related self-efficacy could induce a greater risk for a second ACL injury, using only one cut-off value (reflecting a greater risk for a second ACL injury) for one single scale could be conceptually wrong. If a PRO is sensitive in predicting a second ACL injury, future studies might need to use two different cut-off values: taking K-SES as an example, one cut-off reflecting an extremely high knee-related self-efficacy, and one cut-off reflecting an extremely low knee-related self-efficacy. Notably, some patients returned to the pre-injury Tegner level as early as four months after the ACL reconstruction. It is unclear how this might have affected the results. A further possible limitation of this study concerns age as the ACL-RSI has been reported to be more sensitive for change in younger patients (< 20 years) who go on to suffer a second ACL injury. Patients in this cohort were on average 24.8 years, and it is not known whether the calculated cut-offs are influenced by age, and if age-specific cut-offs may be better to predict second ACL injuries.

CONCLUSION

The determined cut-off values for three commonly used psychological PROs could not differentiate patients who suffered a second ACL injury from those who did not within two years from RTS, regardless of whether the patients achieved symmetrical quadriceps strength or not, in a cohort of patients who had undergone with ACL reconstruction. Therefore, clinicians are recommended to not only rely on cut-off values or a single PRO of those analyzed in this study when making decisions on which patients are at risk of experiencing a second ACL injury when returning to sports after ACL reconstruction.

ACKNOWLEDGMENTS

We would like to thank Editage (www.editage.com) for English language editing, and Bengt Bengtsson at Statistiska Konsultgruppen for the help with statistical analysis.

CONFLICT OF INTEREST

Authors declare no conflict of interest.

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REFERENCES


Glenohumeral Instability and Arm Pain in Overhead Throwing Athletes: A Correlational Study

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Doug Creighton
Carter Kovalcik

1 Overhead Athletic Institute, 2 Physical Therapy, Oakland University

Keywords: Glenohumeral, instability, hypermobility, overhead throwing athletes, baseball pitchers, Load and Shift Assessment, FAST, KJOC, pain

International Journal of Sports Physical Therapy

Background
The overhead activity of throwing a baseball is arguably the most demanding athletic endeavor placed on the glenohumeral (GH) joint. Previous studies illustrate that 75-80% of baseball players will experience some degree of upper extremity (UE) pain. GH instability is thought to play a role.

Purpose
The purpose of this study was to investigate the relationship between GH joint hypermobility and instability with measures of arm pain and performance in overhead throwing athletes.

Methods
Active competing baseball pitchers were recruited and evaluated once with the anterior-posterior Load and Shift examination procedure, the Kerlan-Jobe Orthopedic Clinic Shoulder and Elbow Questionnaire (KJOC), and the Functional Arm Scale for Throwers (FAST). Multivariate analysis was performed to identify correlation between severe GH capsular laxity (GH instability), mild capsular laxity (GH hypermobility), no capsular laxity (GH normal), and presence of shoulder pain when pitching.

Study Design
Cross-sectional Study.

Results
Forty-five pitchers were evaluated, 62.2% of throwing shoulders were classified normal stability, 26.7% were classified hypermobile, and 11.1% were classified unstable. Average KJOC scores for pitchers with the three mobility categories were 66.1 (normal), 59.7 (hypermobile), and 45.0 (unstable). Average FAST scores among the pitchers were 19.9 (normal), 34.2 (hypermobile), and 32.2 (unstable). Pitchers with GH instability and GH hypermobility demonstrated increased arm pain compared to athletes with normal GH joints; KJOC scores of 3.2, 5.5, and 7.4 (p = 0.0007), respectively.

Conclusion
Pitchers with GH instability and hypermobility demonstrated significantly increased ratings of arm pain compared to pitchers with no capsular laxity.

Level of Evidence
3b

INTRODUCTION

Background
Prevention of baseball throwing-related injuries and identification of potential risk factors for pain and injury in overhead throwing athletes is a topic of interest for physical therapists, athletic trainers, physicians, and other medical providers involved in the care and treatment of these athletes. Prevention of throwing related injuries is imperative considering current trends in injury and the incidence of surgery to the shoulder and elbow in young athletes. Up to 50% of youth pitchers between nine and 14 years old experience arm pain. Analysis of 241 shoulder injuries and 150 elbow injuries in high school baseball players revealed that 93.5% and 88.0% of shoulder and elbow injuries, respectively, were throwing related injuries. In addition, the risk
of injury increases with increasing levels of competition.\textsuperscript{3,4} Youth throwing-related injuries pose problems to participation and competitiveness in sport, and may also result in long-term pain and increased incidence of degenerative change to the throwing shoulder and elbow.\textsuperscript{5}

Both translatory and angular motion changes occur in the shoulders of throwing athletes.\textsuperscript{6,7} The dominant shoulders of pitchers have been shown to demonstrate greater amounts of anterior and posterior translation than the nondominant shoulders.\textsuperscript{7} Additionally, angular range of motion changes occur in the dominant shoulder of pitchers with increased external rotation of 5 to 15 degrees and decreased internal rotation of 5 to 20 degrees compared to the nondominant shoulder.\textsuperscript{7–9} These changes have been observed in athletes younger than 12 years old, and occur secondary to humeral retroversion, soft tissue changes, and other joint-related adaptations such as glenoid retroversion or labral tearing.\textsuperscript{6–10}

It has been shown that glenohumeral (GH) instability contributes to shoulder pain and injury in athletes of various sports.\textsuperscript{1,11,12} Chronic instability plays a role in degenerative conditions at the shoulder, including the development of osteochondral defects, capsuloligamentous enlargement and tearing, labral deformation, and tendinopathy.\textsuperscript{13–15} Currently, it is not fully understood how the presence of GH instability or hypermobility in the throwing shoulders of baseball players influences ratings of pain or the role it may play in throwing arm function. The purpose of this study was to investigate the relationship between GH joint hypermobility and instability with measures of arm pain and performance in overhead throwing athletes.

METHODS

IRB approval was received in the Fall of 2019. Prior to recruiting participants, a categorical inter-rater reliability test of the load and shift assessment was conducted on a cohort of thirty physical therapy students (n=50). This test was to substantiate the researchers’ ability to perform and reliably assess shoulder stability with the Load and Shift test. The results of this test were compared to the results of a board-certified, fellowship-trained orthopedic physical therapist who has been a practicing clinician and educator for 37 years. The ICC value for the two researchers who later conducted the Load and Shift test on the participants in this study was found to be .81 and .85 in comparison to the aforementioned clinician, demonstrating good reliability.

PARTICIPANTS

Baseball pitchers (n=45) trained at the Overhead Athletic Institute were recruited to participate in this study. All participants met the inclusion criteria of being male and currently competing in baseball. Participants were excluded from this study if they reported having undergone surgery within the prior 12 months, were under the age of 13 or over the age of 30 years old or were not currently competing due to injury. Participants were asked to report any history of previous arm injury.

CONSENT

Prior to participation, subjects and/or their parents/guardians (for those under 18 years old) were informed about the aim of this study and that their consent would be necessary to participate. Pitchers under 18 years old required parent/guardian permission as well as personal assent. All participants and/or their parents/guardians were provided informed written consent prior to testing. This study was approved by the Oakland University Institutional Review Board: IRB Protocol # 1902.004.

OBJECTIVE MEASURES OF ARM PAIN AND DYSFUNCTION

TESTING PROCEDURES

Following obtaining informed consent, a consistent testing procedure was performed. Each participant first was provided the KJOC questionnaire, upon its completion the FAST survey was provided. When the FAST survey was completed the Load and Shift test was conducted on the participant’s throwing shoulder. The Load and Shift test was conducted with the participant seated on a treatment table, the participant was instructed to gently lift their chest as to be positioned in a more erect posture and to relax their throwing arm, allowing it to hang by their side. The researcher, standing in front of the participant, then stabilized scapula posteriorly and clavicle anteriorly with one hand and while grasping humeral head with the other hand by gradually compressing through the soft tissues (Figure 1). Mid-range anterior and posterior translatory oscillations of the humeral head were performed followed by anterior translation and posterior translation into tissue resistance. No surveys, KJOC or FAST, were analyzed by the researchers prior to the application of the Load and Shift test.

KERLAN JOBE ORTHOPEDIC CLINIC SURVEY (KJOC)

To quantify arm pain and dysfunction, participants completed the Kerlan-Jobe Orthopedic Clinic Shoulder and Elbow Questionnaire (KJOC), which is a Patient-Reported Outcomes (PRO) Scale. The KJOC scale evaluates the functional status of the upper extremity (UE) in overhead athletes. It includes 10 items divided into three categories: impact of injury on function and athletic performance (five items), UE symptoms (four items), and interpersonal relationships related to performance (one item). The responses are recorded using a visual analog scale, where a mark is placed along a 10-cm line indicating the athlete’s current level of physical function. The KJOC’s scores range from 0-100 with lower scores indicating greater disability. The KJOC demonstrated excellent reliability and can distinguish between athletes with or without shoulder or elbow pain.\textsuperscript{16,17} The KJOC has been used as an effective means of assessing arm pain and injury in collegiate and profes-
sional throwing athletes and shows good correlation with the Youth Throwers Scale in adolescents.18–22

THE FUNCTIONAL ARM SCALE FOR THROWERS (FAST)

To further investigate the functional status of the participants’ arm, a second PRO scale, the FAST, was also collected. The FAST is a 22-item PRO scale that includes five subscales: pain (six items), throwing (10 items), ADL (five items), psychological impact (four items), and advancement (three items). There is also an additional nine-item module specifically for pitchers. Higher FAST scores indicated greater disability. The FAST demonstrated excellent test-retest reliability (ICC, 0.91–0.98), acceptable correlation with the DASH (ICC = .49–.82) and KJOC (ICC = 0.62–0.81) scores and classified 85.1% of players into the correct injury group. The FAST has been validated as an effective PRO scale in adolescent and adult throwing athletes.23,24 For UE injury status, the FAST proved 91% sensitivity and 75% specificity. The FAST is a valid and reliable tool for assessing reported health care outcomes in throwing athletes with injury.24

LOAD AND SHIFT TEST

The Load and Shift (L-S) test has proven to be a valid and reliable means of assessing GH joint mobility.25 The accuracy of the L-S test has been validated in comparison to MRI arthromograms of the shoulder by van Kampen et al.26 The L-S test has been demonstrated to be 84% accurate in diagnosis of labral tearing and shoulder instability compared to MRI arthrogram.26

To assess the degree of shoulder instability present in the participants of this study, the L-S test was performed on all participants, as shown in Figure 1. The researcher graded the participant as normal, hypermobile, or unstable. During the L-S assessment, the GH joint was classified normal if it displayed minimal anterior and posterior translation with an intact and stable capsule. The GH joint was classified as hypermobile if it displayed a great amount of anterior or posterior translation and the capsule was less firm with no immediate stop in translatory motion. Finally, the GH joint was classified unstable if the head of the humerus could not be easily subluxed over the edge of the glenoid labrum, in either an anterior or posterior direction, during the L-S assessment.27

STATISTICAL ANALYSIS

Mean and variance values were calculated for age, total score of the KJOC and FAST (the cumulative result of all survey questions for both the KJOC and FAST), and arm pain. One-way Analysis of Variance (One-way ANOVA) was performed to identify any correlation between GH articulation of unstable, hypermobile, or normal and self-reported measures of shoulder and elbow performance and discomfort. Question 2 on the KJOC, "How much arm pain do you experience in your throwing shoulder or elbow?" was used to assess arm pain from the KJOC questionnaire. Question 2 on the FAST, "How painful is your arm during 'game-speed' throwing?" was used to assess arm pain from the FAST survey.

Independent t-tests with unequal variances were used to test for differences in total KJOC and total FAST scores between baseball pitchers with unstable and normal shoulders and between athletes with and without a history of injury, which was recorded by the participant as part of the KJOC questionnaire. Statistical analyses were performed using Microsoft Excel Statistics Data Analysis ToolPak (Microsoft, Albuquerque, NM), alpha level of p ≤ 0.05.

RESULTS

Forty-five baseball pitchers, ages 13–25 years old, mean age of 15.98 ± 2.82 were included in this cross-sectional study. Distribution of participants by age ranged from 13–25 years old. Arm dominance was recorded, with n=56 for right-handed throwers and n=9 for left-handed throwers. These descriptive statistics are presented in Table 1.

SHOULDER STABILITY, ARM PAIN, AND ARM FUNCTION

Eleven percent (n=5) of throwing shoulders were found to be unstable, 26.7% (n=12) were found to be hypermobile, and 62.2% (n=28) were found to be normal. Total KJOC score means were found to be 66.1 ± 18.4, 59.7 ± 18.0, and 45.0 ± 20.1 for normal, hypermobile, and unstable shoulders, respectively. Total FAST score means were found to be 19.9 ± 14.6, 34.2 ± 18.1, and 32.1 ± 11.2 for normal, hypermobile, and unstable shoulders, respectively. Pitchers with normal shoulders exhibited significantly higher levels of function than pitchers with unstable and hypermobile shoulders when measured with the FAST, as demonstrated in Table 2. Pitchers with normal shoulders exhibited significantly higher levels of function than pitchers with unstable shoulders when measured with the FAST and KJOC, as demonstrated in Table 3. Pitchers with normal shoulders exhibited significantly less arm pain than pitchers with unstable and hypermobile shoulders in both the FAST and KJOC, as demonstrated in Table 4.
Table 1. Descriptive Demographics - Baseball Pitchers (total n=45, all were male, 36 were right hand dominant while 9 were left hand dominant)

<table>
<thead>
<tr>
<th>Age</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
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<tr>
<td>16</td>
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<td>17</td>
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<tr>
<td>19</td>
<td>1</td>
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<tr>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
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<tr>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
</tr>
</tbody>
</table>

PREVIOUS HISTORY OF INJURY

A previous history of injury was noted in 80% (n=36) of the participants in the study. When comparing total KJOC scores of pitchers with a history of arm injury to pitchers with no history of arm injury, healthy pitchers scored 71.9, while pitchers with a history of injury scored 59.6 (p=0.029). These scores indicate reduced subjective ratings of function in pitchers with a history of arm injury. When FAST scores of pitchers with a history of injury were compared to pitchers with no history of injury, there was no statistically significant difference (p=0.095); healthy pitchers scored 16.6 while athletes with a history of injury scored 27.2.

DISCUSSION

The aim of this study was to determine if there is a correlation between measures of GH hypermobility and subjective reports of arm pain and impairment during pitching. Current literature suggests that baseball pitchers have greater GH translation and greater angular motion in their throwing shoulder compared to the non-throwing shoulder.7 Hypermobility and instability have correlated with increased reports of pain and impairment in other sports.1,12 The presence of joint instability and angular hypermobility has also been correlated to the development numerous orthopedic conditions including capsular strains, labral tears, internal impingement, tendinopathy, and other degenerative conditions such as osteochondral defects.14,28,29

Examination for excessive capsular laxity and labral instability is possible with the application of the L-S test.25–27 Given this, the authors believe there is a need for greater player and parental awareness of this examination procedure and the potential adverse effects of GH hypermobility on the throwing shoulder. Perhaps athletic trainers and physical therapists trained in the application of the L-S procedure could offer optional pre-season screening exams at facilities where private pitching lessons occur and at local high schools and colleges. If capsular laxity or instability is found, therapeutic advice regarding joint hypermobility, pitch count limits, the benefits of stabilization exercise, or perhaps referral to an orthopedist could be provided to that athlete.

The shoulder undergoes massive loading during the acceleration phase of the throw and immediately after ball release. Fleisig and colleagues found that in adult pitchers’ shoulders undergo 380N of anterior force during acceleration and 400N of posterior force and 1080N of compressive force immediately after ball release.30 GH instability or excessive joint translation in the presence of these large loads has the potential to damage stabilizing structures of the shoulder such as the labrum and the capsule. Excessive angular motion during the late cocking phase of the throw has been shown to increase the likelihood of capsular strains, SLAP lesions, and internal impingement.28,31 At present, the literature does not address changes in glenohumeral translatory motion and the role this may play in shoulder pain and performance during overhead throwing. This current study examined the potential importance of this type of passive joint motion in evaluation overhead throwing athletes. The results demonstrated an association between increased passive joint translation (GH hypermobility and instability) and increased pain perception and throwing performance impairment.

LIMITATIONS

This study evaluated overhead throwing athletes (baseball pitchers) with a mean age of 15.98 years of age, as such, the current findings may not apply to more physically mature collegiate and professional baseball pitchers. The authors believe that this study should be replicated on a larger number of older baseball pitchers such as those competing at the professional and collegiate levels. Additionally, the number of subjects (n=45), may impact the generalizability of the findings.

Table 2. Analysis of Variance of Total KJOC and FAST Scores and Glenohumeral Mobility, reported as mean ± SD,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
<th>Hypermobile</th>
<th>Unstable</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAST Total</td>
<td>19.9 ± 14.6</td>
<td>34.2 ± 18.1</td>
<td>32.1 ± 11.2</td>
<td>0.025</td>
</tr>
<tr>
<td>KJOC Total</td>
<td>66.1 ± 18.4</td>
<td>59.7 ± 18.0</td>
<td>45.0 ± 20.1</td>
<td>0.075</td>
</tr>
</tbody>
</table>

Outcomes are reported in units used by the questionnaire (0-100 for KJOC where higher score indicates better function and less pain and 0-100 for FAST where higher number indicates more pain and less function).
Table 3. Comparison of Normal and Unstable Shoulder Total FAST and KJOC Scores, reported as mean ± SD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
<th>Unstable</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAST Total</td>
<td>19.9 ± 14.6</td>
<td>32.1 ± 11.2</td>
<td>-2.14</td>
<td>0.035</td>
</tr>
<tr>
<td>KJOC Total</td>
<td>66.1 ± 18.4</td>
<td>45 ± 20.1</td>
<td>2.19</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Outcomes reported in units used by the questionnaire (0-100 for KJOC where higher score indicates better function and less pain and 0-10 for FAST where higher number indicates more pain and less function) utilizing paired t testing.

Table 4. Analysis of Variance of Arm Pain Scores in KJOC and FAST and Glenohumeral Mobility, reported as mean ± SD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
<th>Hypermobile</th>
<th>Unstable</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm Pain FAST</td>
<td>2 ± 1.2</td>
<td>3 ± .8</td>
<td>3 ± 1</td>
<td>0.019</td>
</tr>
<tr>
<td>Arm Pain KJOC</td>
<td>7.4 ± 2.2</td>
<td>5.5 ± 2.3</td>
<td>3.2 ± 2.1</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

Outcomes reported in units used by the questionnaire (0-10 for KJOC where lower score indicates more pain, and 0-5 for FAST where higher number indicates more pain).

CONCLUSION

The results of this study indicate that baseball pitchers who exhibit greater amounts of passive anterior and posterior translation of the GH joint as demonstrated by the L-S assessment report higher levels of arm pain and discomfort. Pitchers who demonstrate increased passive humeral head translation at the GH joint also report lower levels of function and performance. Pitchers who showed the greatest amount of instability at the GH joint, as evidenced by manual subluxation of the humeral head during the load and shift assessment, demonstrated the worst overall scores for function and pain. Additional research is needed to determine the association between increased passive humeral head translation, shoulder pain, and throwing performance in other age groups.

CONFLICTS OF INTEREST

The authors of this paper declare that they have no conflicts of interest.

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Development of an Injury Burden Prediction Model in Professional Baseball Pitchers

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Keywords: Prognostic Model, Shoulder, Elbow, Humeral Torsion, Pitch Load

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Background
Baseball injuries are a significant problem and have increased in incidence over the last decade. Reporting injury incidence only gives context to rate but not in relation to severity or injury time loss.

Hypothesis/Purpose
The purpose of this study was to 1) incorporate both modifiable and non-modifiable factors to develop an arm injury burden prediction model in Minor League Baseball (MiLB) pitchers; and 2) understand how the model performs separately on elbow and shoulder injury burden.

Study Design
Prospective longitudinal study

Methods
The study was conducted from 2013 to 2019 on MiLB pitchers. Pitchers were evaluated in spring training arm for shoulder range of motion and injuries were followed throughout the season. A model to predict arm injury burden was produced using zero inflated negative binomial regression. Internal validation was performed using ten-fold cross validation. Subgroup analyses were performed for elbow and shoulder separately. Model performance was assessed with root mean square error (RMSE), model fit (R2), and calibration with 95% confidence intervals (95% CI).

Results
Two-hundred, ninety-seven pitchers (94 injuries) were included with an injury incidence of 1.15 arm injuries per 1000 athletic exposures. Median days lost to an arm injury was 58 (11, 106). The final model demonstrated good prediction ability (RMSE: 11.9 days, R2: 0.80) and a calibration trend of 0.98 (95% CI: 0.92, 1.04). A separate elbow model demonstrated weaker predictive performance (RMSE: 21.3; R2: 0.42; calibration: 1.25 [1.16, 1.54]), as did a separate shoulder model (RMSE: 17.9; R2: 0.57; calibration: 1.01 [0.92, 1.10]).

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Conclusions

The injury burden prediction model demonstrated excellent performance. Caution should be advised with predictions between one to 14 days lost to arm injury. Separate elbow and shoulder prediction models demonstrated decreased performance. The inclusion of both modifiable and non-modifiable factors into a comprehensive injury burden model provides the most accurate prediction of days lost in professional pitchers.

Level of Evidence

INTRODUCTION

Baseball injuries are a significant problem with increased incidence over the last decade.1–3 The greatest injury incidence is to the elbow and shoulder,1,4 with orthopaedic surgery signifying a significant proportion of injuries.5 These injuries have a substantial medical,6 financial,7 and psychological burden8 on the individual and team.9 Due to the significance of these injuries,6,7 individual physical risk factors have been recognized to assist clinicians in identifying baseball players at risk for arm injury.9–12 However, these methods are limited by their simplicity, without accounting for the complex interrelated nature of modifiable and non-modifiable relationship to baseball injuries.13,14

While identifying individuals at risk for injury can improve athlete injury outcomes,9 this does not give a complete clinical perspective. Reporting injury incidence only gives the rate but not injury severity or associated time loss.9 For example, the professional baseball shoulder and elbow injury incidence is 1.4 and 0.9 injuries per 1000 athlete exposures, respectively,15 but elbow injuries have over six times more days missed compared to shoulder injuries.16 Simply identifying baseball players at risk for injury would give equal weight to shoulder and elbow injuries and additionally would not distinguish between minor and severe injuries.8 Severity and site of injury will relate to the requirement for surgical interventions, including reconstruction, and hence time loss, highlighting the need to assess these parameters.17

Further, considerations must be given to the unbalanced nature of injury data, as the majority of athletes will report no injuries (i.e., no days lost), with a sparse number sustaining severe injuries, providing greater complexity to injury burden data.18 Pinpointing potential high injury burden athletes (pitchers) would allow for improved resource consolidation.8 Due to the continued rise in pitching injuries,1,2 and the incomplete clinical context of the identified injury risk factors,16 there is a need to distinguish pitchers at increased risk for greater comprehensive arm injury burden.

Pitching is a series of coordinated movements that involve the entire body.19 The interplay between modifiable and non-modifiable intrinsic and extrinsic factors in determining injury risk and burden signify the intricacies of this problem.13 The complex nature of pitching injuries require in depth examination, reasoning, and clinical decisions.20 However, while sports medicine clinicians have advanced skills and reasoning,21 there continues to be ambiguity in determining true risk.22 A more complex approach to identify at risk athletes has been proposed,23 involving the assessment of modifiable and non-modifiable factors as a whole.23–25 One method that incorporates this approach is via risk prediction models.26 Prediction models are statistical models that combine multiple predictors to estimate an individual’s risk of an event.27–29 These tools are not designed to supersede clinical experience and decisions; rather, assist in determining the best actions (or inaction) for patients.26 Prediction models have been used extensively in clinical medicine, such as whether to prescribe of cholesterol lowering therapies through the Framingham cardiovascular risk score.30

Quantifying complex systems through prediction models is needed to enumerate injury burden.24 These predictions can be used by clinicians and other healthcare professionals to better identify baseball players at risk for a high injury burden,31 and subsequently improve injury identification.32 Therefore, the purpose of this study was to 1) incorporate both modifiable and non-modifiable factors to develop an arm injury burden prediction model in Minor League Baseball (MiLB) pitchers; and 2) understand how the model performs separately on elbow and shoulder injury burden.

MATERIALS AND METHODS

STUDY DESIGN

A prospective longitudinal study was conducted from 2013 to 2019 on MiLB pitchers in one Major League Baseball (MLB) organization. Prior to testing, the risk and benefits of participation were explained in verbal and written form to all participants. Participants were tested at the beginning of spring training (pre-season). All test administrators were blinded to hand dominance.33 Participants were tested for shoulder range of motion (ROM) and humeral torsion (HT). Following testing, participants were followed for the entire season for total athletic exposures and arm injuries. Each pitcher was incorporated into each individual season. If a pitcher played multiple seasons, each season was an individual observation. If a pitcher sustained an injury, the pitcher was no longer included in observation for the next season. All participant information was de-identified and coded into an encrypted centralized database. This investigation received favorable ethics approval from the University Institutional Review Board.
PATIENT PUBLIC INVOLVEMENT

Sports medicine clinicians, performance professionals, and coaches within the organization were included in determining the variables to be collected. Presentations were performed for organizational stakeholders throughout data collection and prediction model development.

PARTICIPANTS

Participants were included if they were able to participate in all practices and competitions and were under a MiLB contract. Participants were excluded if they were currently injured or not participating in all spring training activities, participating in MLB spring training at time of data collection, or signed a professional contract in the middle of the season (e.g., draft, free agent, or international signing).9

SHOULDER RANGE OF MOTION AND HUMERAL TORSION

Shoulder external (ER), internal (IR), horizontal adduction (HA) range of motion (ROM) was measured using previously described methods.34–37 Internal reliability testing demonstrated excellent reliability for shoulder ER (intraclass correlation coefficient (ICC) (2,1) =0.99; Standard error of measure (SEM) = 2.0; ICC (2,K) = 0.99; SEM= 0.95), IR (ICC (2,1)= 0.97; SEM = 2.5; ICC (2,K) = 0.97 SEM= 2.6), and HA (ICC (2,1) = 0.99; SEM = 2.59; ICC (2,K) =0.97; SEM = 1.2). Shoulder ER and IR were summed to measure shoulder total ROM (TROM). Humeral torsion (HT) were measured with a 5-MHz transducer (Sonosite Inc., Bothell, WA, USA) with previously described methods.10 HT testing demonstrated excellent reliability (ICC (2,1) = 0.97; SEM = 2.5; ICC (2,K) = 0.97 SEM= 2.6). Two data collection trials were performed per shoulder and the data collection trials were averaged for analyses.38 For further explanation of the methods, please refer to the Appendix 1.

EXPOSURE

Baseball (i.e., athlete) exposure was defined as number of days participating in training, practice, or games in a season.39 Pitching exposure was defined as the total number of pitches within a season.39

OUTCOME DEFINITION

An injury was defined as an injury to a tendon, ligament, nerve, muscle, or bone that occurred during any baseball team sponsored activity or event and was followed by at least one day of missed practice or baseball games.35 If a player was unavailable to play for injury prevention reasons (i.e., has reached league or individually determined pitch or innings count limits), then their absence was not considered as an injury. Injuries were defined by the Orchard Sports Injury Classification system and arms injuries stratified by shoulder/clavicle, upper arm, elbow, and forearm.40 All other injuries and illness were also recorded, and time loss was not taken into account for overall exposure, nor included in the injury burden analyses. Arm injury burden was defined as the product of incidence and severity.8 Arm injury burden was quantified as the total number of days lost to arm injury in one baseball season.8

Residual inspection demonstrated model instability above 90 days lost to arm injury. Following research team and MLB organizational discussion, time loss to arm injury was truncated to 90 days. In other words, if a player sustained an injury of 120 days, within the model, this would be included at 90 days.

STATISTICAL ANALYSES

All data were investigated for missingness prior to analyses using the R package naniar. Missing data was low (3% of entire cohort had one or more missing values), thus complete case analyses were performed. Participant characteristics were described using mean (standard deviation) for continuous normally distributed variables, median (interquartile range) for non-normally distributed continuous variables, and frequencies and percentages for categorical variables. Arm injury incidence was calculated by sum of arm injuries divided by sum of baseball (i.e., athlete) exposures (AE) multiplied by 1000. For expanded statistical analyses description, please refer to Appendix 2.

Linearity was not assumed, and prior to model development, continuous variables were assessed for non-linearity in relation to the outcome of days lost to arm injury. All predictors were observed to have linear relationships.

SAMPLE SIZE CALCULATION

An a priori sample size calculation was performed prior to model development.41 It should be noted that this sample size method does not explicitly cover zero inflated models. During the study period, a total of 297 pitchers met inclusion criteria, therefore a maximum of 26 parameters (i.e., the number of degrees of freedom) could be included in the development of the injury burden prediction model. The R package pmsampsize was used to calculate the required sample size.

MODEL DEVELOPMENT: PRIMARY ANALYSIS

To predict the number of days lost (up to 90 days) to arm injury in professional pitchers a zero inflated negative binomial regression model was utilized.42 An alternative model, a hurdle model was developed, to demonstrate similar prediction performance (Appendix 5). Predictor variables included were chosen based on the baseball injury prevention literature and included: 1) age, 2) BMI, 3) pitching role (starter versus reliever), 4) seasonal number of pitches, 5) number of pitching appearances in a season, 6) HT difference between dominant and nondominant shoulder (in degrees), 7) dominant shoulder TROM (in degrees), 8) dominant HA (in degrees), 9) lower extremity or trunk injury in the same year, 10) any previous arm injury history, 11) years played professionally, 12) received individualized injury prevention programs, 13) continent of origin, and 14) days practiced and competed in the season (exposure).9,43–52 Variable selection was performed using elastic
net penalization, using ten-fold cross-validation.\textsuperscript{53} Internal validation of the model was performed using ten-fold cross validation.\textsuperscript{53} Prediction model performance was assessed by calculating the root mean square error (RMSE), explained variation ($R^2$), and calibration. Calibration is the agreement between predicted and actual risk.\textsuperscript{32} Calibration was assessed by calculating the calibration slope with 95% confidence intervals and graphically plotting the observed values against the predicted values. Subgroup analyses were performed for elbow and shoulder separately. A sensitivity analysis was performed with the inclusion of only modifiable predictors to assist clinicians in understanding risk and treatment options including: (1) seasonal number of pitches, 2) number of pitching appearances in a season, 3) dominant shoulder TROM (in degrees), 4) dominant HA (in degrees), 5) received individualized injury prevention programs, 6) days practiced and competed in the season (exposure). All analyses were performed in R version 3.5.1 (R Core Team 2013). The R package psc1 was used for zero inflation modelling and mpath for elastic net. For full code, please see Appendix 4.

Reporting of this study followed the transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD) recommendations.\textsuperscript{54}

RESULTS

PARTICIPANT CHARACTERISTICS

A total of 297 pitchers were included (age: 23.0 (2.2) years, BMI: 24.8 (2.2), left handed: 21%). A total of 84 pitchers reported an arm injury during data collection. Overall arm injury incidence was 1.15 arm injuries per 1000 AE’s, 0.5 elbow injuries per 1,000 AE’s, and 0.8 shoulder injuries per 1,000 AE’s (Table 1). Median days lost to an arm injury was 58 (11, 106).

ARM INJURY BURDEN PREDICTION MODEL

Model development following tenfold internal validation demonstrated a RMSE of 11.9 days, 0.80 $R^2$, and a calibration slope of 0.98 (95% CI: 0.92, 1.04); Figure 1. Full model equation is reported in Table 2.

The zero-inflated negative binomial model incorporates two models (count and zero) into one comprehensive model. As such, the count and zero model should be considered one model

ELBOW INJURY BURDEN PREDICTION MODEL

Elbow injury burden model development demonstrated a RMSE of 21.3 days, 0.42 $R^2$, and a calibration slope of 1.25 (95% CI: 1.16, 1.34; Figure 2).

SHOULDER INJURY BURDEN PREDICTION MODEL

Shoulder injury burden model development demonstrated a RMSE of 17.9 days, 0.57 $R^2$, and a calibration slope of 1.01 (95% CI: 0.92, 1.10; Figure 3).

SENSITIVITY ANALYSIS

The inclusion of only modifiable predictors within the prediction model decreased performance compared to the original model (RMSE: 21.2, $R^2$: 0.42, Calibration: 1.12 (95% CI: 0.99, 1.25).

DISCUSSION

SUMMARY

This prediction model demonstrated excellent performance, as demonstrated by the high $R^2$ and calibration slope. Due to the model error of 12 days, predictions of one to 14 days should be interpreted with caution. Stratifying by predicting individual elbow or shoulder burden decreased prediction model performance. Including only modifiable predictors demonstrated decreased prediction performance.

CLINICAL IMPLICATIONS

Clinicians integrate a plethora of skills, tools, and experience to keep athletes on the field.\textsuperscript{53} The complexity associated with examination and performance, including advances in technology,\textsuperscript{56} load monitoring,\textsuperscript{57} and rehabilitation and performance testing,\textsuperscript{25} necessitates the need employ these tools and information. Within baseball, athletes are physically examined in spring training and traditionally this information is used to assess each individual risk factor.\textsuperscript{9} This prediction model incorporated multiple predictors into one cohesive model to calculate a predicted number of days lost to arm injury, ranging from 0 to 90. These individual injury burden predictions are meant to help reduce complexity of a difficult issue through clarifying prognosis,\textsuperscript{58} to improve a clinician’s ability to care for their patients.

This model reported an RMSE of 12 days. What this means clinically is that for any predicted days of injury burden, the actual number of days lost to injury will be within 12 days of the predicted value. While an error rate of 12 days for higher burden injuries (i.e., $>50$ days) may not alter clinical interpretation, a difference between 0 and 14 days could affect clinical decisions. To give an example, if the model predicted 3 days lost to injury, the days lost could be between one and 15 days. This would be clinically interpreted as a minor to moderate arm injury. On the other hand, if a pitcher was predicted to have 60 days lost to injury, a 12 day difference (48 to 72 days) would not affect clinical decisions. The pitcher would still be identified as a pitcher who could sustain a serious arm injury during the season. These findings suggest that this injury burden model can help identify pitchers who are at risk for sustaining a high injury burden during the season. However, these models should be interpreted with caution for predicted injury burden for one to 14 days.
Table 1. Characteristics of the pitchers included in the study. Values are percentages unless stated otherwise.

<table>
<thead>
<tr>
<th></th>
<th>All Pitchers (n = 297)</th>
<th>Non-Arm Injured Pitchers (n = 203)</th>
<th>Arm Injured Pitchers (n = 94)</th>
<th>Elbow Injury (n = 40)</th>
<th>Shoulder Injury (n = 64)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (SD) Age (years)</td>
<td>23.0 (2.2)</td>
<td>22.8 (2.2)</td>
<td>23.2 (2.0)</td>
<td>23.2 (2.4)</td>
<td>22.8 (2.1)</td>
</tr>
<tr>
<td>Hand Dominance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>61%</td>
<td>63%</td>
<td>58%</td>
<td>60%</td>
<td>64%</td>
</tr>
<tr>
<td>Right</td>
<td>39%</td>
<td>37%</td>
<td>42%</td>
<td>40%</td>
<td>36%</td>
</tr>
<tr>
<td>Mean (SD) BMI (kg/m2)</td>
<td>24.8 (2.2)</td>
<td>24.6 (2.3)</td>
<td>24.8 (2.1)</td>
<td>25.1 (2.3)</td>
<td>24.9 (2.3)</td>
</tr>
<tr>
<td>Pitching Role</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting Pitcher</td>
<td>55%</td>
<td>52%</td>
<td>62%</td>
<td>52%</td>
<td>58%</td>
</tr>
<tr>
<td>Relief Pitcher</td>
<td>45%</td>
<td>48%</td>
<td>38%</td>
<td>48%</td>
<td>42%</td>
</tr>
<tr>
<td>Continent of Origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td>71%</td>
<td>66%</td>
<td>83%</td>
<td>68%</td>
<td>80%</td>
</tr>
<tr>
<td>Latin America</td>
<td>29%</td>
<td>34%</td>
<td>17%</td>
<td>32%</td>
<td>20%</td>
</tr>
<tr>
<td>Years within Professional Baseball</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-2 years</td>
<td>73%</td>
<td>80%</td>
<td>57%</td>
<td>42%</td>
<td>58%</td>
</tr>
<tr>
<td>3-4 years</td>
<td>22%</td>
<td>3%</td>
<td>33%</td>
<td>46%</td>
<td>32%</td>
</tr>
<tr>
<td>5+ years</td>
<td>5%</td>
<td>1%</td>
<td>11%</td>
<td>12%</td>
<td>10%</td>
</tr>
<tr>
<td>Mean (SD) Seasonal Pitch Load</td>
<td>900 (657)</td>
<td>991 (643)</td>
<td>548 (615)</td>
<td>468 (594)</td>
<td>572 (609)</td>
</tr>
<tr>
<td>Mean (SD) Dominant Total Range of Motion in degrees</td>
<td>160 (13)</td>
<td>159 (13.2)</td>
<td>159 (11.8)</td>
<td>162 (12)</td>
<td>159 (14)</td>
</tr>
<tr>
<td>Mean (SD) Dominant Horizontal Adduction in degrees</td>
<td>-2.3 (12.2)</td>
<td>-2.8 (11.9)</td>
<td>-1.1 (14.6)</td>
<td>-1.4 (12.6)</td>
<td>-0.2 (13.2)</td>
</tr>
<tr>
<td>Mean (SD) Humeral Torsion Difference in degrees</td>
<td>18.2 (13.7)</td>
<td>18.5 (13.5)</td>
<td>16.2 (11.9)</td>
<td>17.3 (13.4)</td>
<td>15.9 (12.8)</td>
</tr>
<tr>
<td>Kinematic Chain Injury</td>
<td>15%</td>
<td>3%</td>
<td>11%</td>
<td>5%</td>
<td>13%</td>
</tr>
</tbody>
</table>

Total range of motion = Sum of shoulder external and internal rotation range of motion
Humeral torsion difference is calculated as dominant – nondominant shoulder

INDIVIDUAL ELBOW AND SHOULDER MODELS

Elbow and shoulder injury burden models demonstrated decreased performance compared to the primary model and had reduced sample sizes therefore, should be interpreted with caution. The discrepancies between elbow and shoulder injury burden may decrease the performance of these models. Elbow and shoulder injuries can have different risk factors, with mechanisms of injury occurring during different points within the pitching motion. Different clinical interventions may be required to reduce shoulder verses elbow injury risk. The contrasting injury burden risk factors between shoulders and elbows may decrease the prediction precision of individual shoulder or elbow models. Future research is required to develop separate shoulder and elbow burden prediction models.

INCLUSION OF ONLY MODIFIABLE PREDICTORS

Including only modifiable predictors demonstrated decreased injury burden prediction compared to the inclusion of modifiable and non-modifiable predictors. Previous work has called for the inclusion of both modifiable and non-modifiable predictors to improve understanding and ultimately decrease sports injuries. However, while this has been proposed for many years, the majority of current evidence only includes isolated modifiable factors when assessing injury risk. As these results suggest, without the inclusion of non-modifiable predictors, clinicians are inhibited from having an improved understanding of current injury risk. While it may seem from a clinical perspective that including non-modifiable predictors does not improve how a clinician will treat a patient, a more comprehensive injury risk examination allows the clinician to better identify athletes at risk for sustaining an injury. These prediction models are not recommended to be used to identify which specific interventions or factors should be the focus of care. Prediction models are not causal, as such, if a particular predictor is "significant" with a specific athlete, this does not mean that particular predictor should be intervened upon. A thorough physical exam and clinical reasoning should be used to identify which tests and measures to intervene on.

STRENGTHS AND POTENTIAL LIMITATIONS

This study utilized a seven-year prospective cohort that was specifically designed to assess arm injuries in professional baseball players. All data collectors were physical therapists, specifically trained and evaluated for reliability in the physical examination techniques, improving the consistency and reliability of these data. Only a small proportion
of data were missing, allowing for a complete case analysis, increasing the validity of these findings. An a priori sample size calculation was performed to create a stable prediction model, increasing the utility of these findings. Internal validation was performed in order to shrink optimism, increasing the generalizability of these results. The full model is reported, increasing transparency and usefulness for future validation. Time lost to injury was truncated at 90 days. Pitchers may be placed on the injured list longer than 90 days; however, truncation was performed at 90 days due to the paucity of players sustaining time loss greater than this time period and the organizational significance of this time period. A small proportion of pitchers were excluded due to participating MLB spring training during data collection. These pitchers were predominantly at the AAA or AA level, decreasing the generalizability of these results to high MiLB players. Injury history was limited to professional baseball seasons and orthopaedic surgery prior to signing a professional baseball contract. As pitchers may sustain arm injuries that last only a few days or a week, there is the potential for residual confounding. All impairment data were collected prior to the season. As predictors can change throughout the season, this decreases the clinical utility of these results. Player salary and signing bonuses were not included in these analyses. As MLB organizational investment may influence time loss to injury, this decreases the precision in these models. This model was not externally validated. It is recommended that external validation should be performed prior to integrating in a clinical setting. This prediction model should be used with caution without further validation.

CONCLUSIONS

This professional baseball injury burden model may have clinical utility in predicting pitchers that are at risk for sustaining a high injury burden within the season. However, caution should be advised with predictions between 1 to 14 days lost to arm injury as this is below the prescribed model error. The inclusion of modifiable and non-modifiable predictors demonstrated improved prediction performance, suggesting that prediction models should include both types of predictors when evaluating injury risk. Separate elbow and shoulder prediction models demonstrated decreased performance and should be interpreted with caution due to low sample size. Further research is required to externally validate this model to understand the generalizability of these findings.
Table 2. Arm Injury Burden Prediction Model.

<table>
<thead>
<tr>
<th>Count Portion of the Model</th>
<th>Coefficient</th>
<th>*95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.62</td>
<td>0.11, 2.10</td>
</tr>
<tr>
<td>Age</td>
<td>-0.02</td>
<td>0.89, 1.05</td>
</tr>
<tr>
<td>Body Mass Index</td>
<td>0.05</td>
<td>0.99, 1.16</td>
</tr>
<tr>
<td>Right Arm Dominance ø</td>
<td>0.04</td>
<td>0.68, 1.72</td>
</tr>
<tr>
<td>Starting Pitcher¥</td>
<td>0.08</td>
<td>0.76, 1.38</td>
</tr>
<tr>
<td>Number of Pitching Appearances</td>
<td>-0.02</td>
<td>0.97, 0.99</td>
</tr>
<tr>
<td>Dominant Shoulder Total Range of Motion</td>
<td>0.01</td>
<td>1.00, 1.03</td>
</tr>
<tr>
<td>Dominant Shoulder Horizontal Adduction</td>
<td>-0.01</td>
<td>0.98, 0.99</td>
</tr>
<tr>
<td>Previous Arm Injury History</td>
<td>0.07</td>
<td>0.61, 1.47</td>
</tr>
<tr>
<td>2 to 4 Years Played Professionally‡</td>
<td>-0.37</td>
<td>0.45, 0.83</td>
</tr>
<tr>
<td>5+ Years Played Professionally‡</td>
<td>0.08</td>
<td>0.60, 2.03</td>
</tr>
<tr>
<td>Received Individualized Injury Prevention Program</td>
<td>-0.11</td>
<td>0.55, 1.01</td>
</tr>
<tr>
<td>Continent of Origin§</td>
<td>0.06</td>
<td>0.76, 1.08</td>
</tr>
<tr>
<td>Exposure Days</td>
<td>-0.006</td>
<td>0.98, 0.99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zero Portion of the Model</th>
<th>Coefficient</th>
<th>*95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-5.82</td>
<td>0.00, 8.99</td>
</tr>
<tr>
<td>Right Arm Dominance ø</td>
<td>-0.21</td>
<td>0.01, 1.87</td>
</tr>
<tr>
<td>Starting Pitcher¥</td>
<td>-0.06</td>
<td>0.15, 1.78</td>
</tr>
<tr>
<td>Number of Pitching Appearances</td>
<td>0.01</td>
<td>0.97, 1.08</td>
</tr>
<tr>
<td>Kinematic Chain Injury</td>
<td>0.86</td>
<td>2.12, 7.33</td>
</tr>
<tr>
<td>Continent of Origin§</td>
<td>0.07</td>
<td>0.74, 1.16</td>
</tr>
<tr>
<td>Exposure Days</td>
<td>0.05</td>
<td>1.03, 1.07</td>
</tr>
</tbody>
</table>

The zero-inflated negative binomial model incorporates two models (count and zero) into one comprehensive model. As such, the count and zero model should be considered one model.

95% CI = 95% Confidence Interval
*95% confidence intervals are exponentially transformed
øReference is Left
¥Reference is relief pitcher
‡Reference is 0 to 1 years played professionally
§Reference is North America

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CONFLICTS OF INTEREST

All authors declare no conflicts of interest.

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Figure 2. Calibration Plot of the Elbow Injury Burden Prediction Model.

Calibration is the relationship between predicted and actual probability of the event. Perfect calibration would be a 45-degree line. A calibration line below the blue line is over-predicting risk. A calibration line above the blue line is under-predicting risk.
Figure 3. Calibration Plot of the Shoulder Injury Burden Prediction Model.

Calibration is the relationship between predicted and actual probability of the event. Perfect calibration would be a 45-degree line. A calibration line below the blue line is over-predicting risk. A calibration line above the blue line is under-predicting risk.
REFERENCES


41. Riley RD, Ensor J, Snell KIE, et al. Calculating the sample size required for developing a clinical prediction model. *BMJ.* 2020;368:m441. doi:10.1136/bmj.m441


SUPPLEMENTARY MATERIALS

Appendix 4

Appendix 3

Appendix 2

Appendix 1
Original Research

Injuries and Illnesses Across 10 Years of Canada Games Competitions: 2009 – 2019

Nicole J Chimera1, Danielle Merasty1, Monica R Lininger2

1 Department of Kinesiology, Brock University, 2 Department of Physical Therapy and Athletic Training, Northern Arizona University

Keywords: athlete, epidemiology, incidence, odds of injury

https://doi.org/10.26603/001c.39743

International Journal of Sports Physical Therapy

Background
The Canada Games are a national level competition held every two years alternating between Summer and Winter Games. Participation in elite level athletics, like the Canada Games, have an inherent risk of injury and illness.

Purpose
To analyze the incidence and characteristics of injuries and illnesses during Canada Games competitions from 2009-2019 (primarily) and to understand sex differences in odds of musculoskeletal injury for Summer and Winter Canada Games athletes (secondarily).

Study Design
Descriptive Epidemiology Study

Methods
Using a retrospective cohort, data were abstracted from medical incident reports generated during Canada Games from 2009 – 2019. Data were coded for body part injured and injury type or illness system; injuries were also categorized as acute or chronic.

Results
Across all 10 years of competition, 3160 injuries reported in 8710 male athletes and 3272 injuries reported in 8391 female athletes. Injury incidence was 362.8 and 389.9 per 1000 male and female athletes, respectively. Female athletes had a 1.12 (95% CI: 1.06; 1.19) greater odds of injury and 1.37 (95% CI: 1.20; 1.57) greater odds of illness compared to male athletes. Overall, injury (399.31 vs. 360.31; p < 0.001) and illness (68.67 vs. 47.30; p < 0.001) incidences were higher in Winter Games, compared to Summer Games, per 1000 athletes. When comparing male and female athletes participating in similar sports, sex specific differences exist in odds of both injury and illness.

Conclusions
Male and female athletes competing in Canada Games competitions demonstrate differences in injury and illness incidence and odds of injury. This suggests a need to examine if additional modifiable risk factors may exist, which could contribute to prevention strategies to reduce injury and illness during Canada Games competition.
Level of Evidence

INTRODUCTION

The Canada Games, which are the highest level of national competition for Canadian athletes, were first held in 1969 and occur every two years, alternating between Summer and Winter games. Participation in elite level competitions, such as the Canada Games, encourages large scale participation in multiple sports over the course of a set time period. While athletic participation of this magnitude and level is desirable for many athletes, there are inherent risks of injury for participants. Following the Sequence of Prevention model, in order to prevent injuries, researchers must first identify and describe the injury problem(s).

To better understand the injury problem, surveys were first conducted during international sports competition in 2004 and included injury data from the Olympic Games and International Federation of Association Football tournaments held between 1998–2001. Injury surveillance programs are now used widely at the organizational level, while numerous studies of injury/illness incidences are reported at both the national level and international levels of competition. Epidemiological assessments of sport injury can provide direction for injury prevention programs and, when assessed over multiple years, provide insight on how injury patterns/frequencies may change over time. Based on epidemiological data, it has been suggested that athletes participating in athletics should have preventative injury intervention focused on overuse injuries, proper rehabilitation of previous injuries, and be sex specific.

Researchers have reported differences in injury incidence and risk of injury between male and female athletes in international track and field competitions and in collegiate athletes; however, incidence proportions were similar between male and female international athletics championships. To date, one recent study successfully implemented an injury surveillance protocol in Canadian varsity athletes. However, there is a paucity of literature regarding injury and illness incidence during the Canada Games with only one study reporting dental injuries during a single Canada Games competition held over 30 years ago. Therefore, the primary purpose of this study was to analyze the incidence and characteristics of injuries and illnesses during Canada Games competitions from 2009–2019. The secondary purpose of this study was to understand sex differences in odds of musculoskeletal injuries for Summer and Winter Canada Games athletes.

METHODS

STUDY DESIGN

This research utilized a retrospective cohort for a descriptive epidemiological design to assess injury and illness patterns in 10 years of Canada Games participants.

PARTICIPANTS

From 2009 – 2019, 17101 (8710 male; 8391 female) athletes participated in Canada Games competitions held in various cities across Canada. 10169 (5457 male; 4712 female) athletes competed in the Summer Canada Games, which were held in the years 2009, 2013, and 2017 and 6952 (3253 male; 3679 female) athletes competed in Winter Canada Games, which were held in the years 2011, 2015, and 2019. Athletes completed a consent for treatment form; a release for Canada Games to use anonymous medical information was acquired starting in 2015.

PROCEDURES

Following ethics approval for Secondary Analysis of Data through Brock University Research Ethics Board, data were abstracted and de-identified by the Canada Games Council for any individual seeking medical attention during their participation in the Canada Games. Medical attention/encounters were recorded in an electronic medical record (EMR) by various clinicians (i.e., athletic therapist, physiotherapist, chiropractor, physician) working with Canada Games events. Medical attention was defined as assessment of a participant’s medical condition by a qualified medical/healthcare practitioner. Abstracted data, for those seeking medical attention, included the following: subjective information on injury, objective information on injury, injury assessment, type of injury, injury diagnosis, further treatment of injury, action taken, place of treatment, and incident status, as well as participant sex, contingent (province), sport, chief complaint, and assessment date. Data were inclusive of Canada Games from 2009 and 2019. For this study, only the first report of an injury/illness were recorded from the medical incident report. There were reports for follow up (linked through incident numbers), but follow ups were not counted as a new injury. In some instances, there was a medical incident that was linked to an earlier incident report but had an additional or new injury in the follow up incident report. In this case both the initial injury as well as the additional (new) injury reported were included for this analysis.

Using initial and follow up medical incident reports from Canada Games, data were organized based on the International Olympic Committee Injury Surveillance System for categorizing affected injury location, injury type, and illness affected system. Given the data set and the way injuries were reported within the Canada Games EMR, there were three additional injury type categories included beyond those from the International Olympic Committee Injury Surveillance System; these included patellofemoral pain syndrome (PFPS), compartment syndrome, and postural. Injuries were also categorized as acute or overuse. Acute sports injury was defined as “loss or abnormality of bodily structure or functioning resulting from an isolated exposure to physical energy during sports training.
Table 1. Categorization for Injury location, Injury Type, and Illness Affected System

<table>
<thead>
<tr>
<th>Injury Location</th>
<th>Injury Type</th>
<th>Illness Affected System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdomen</td>
<td>Arthritis/synovitis/bursitis</td>
<td>Allergic</td>
</tr>
<tr>
<td>Achilles tendon</td>
<td>Compartment syndrome</td>
<td>Cardiovascular</td>
</tr>
<tr>
<td>Arm (Upper)</td>
<td>Concussion</td>
<td>Dermatologic</td>
</tr>
<tr>
<td>Ankle</td>
<td>Contusion/haematoma/bruise</td>
<td>Endocrinological</td>
</tr>
<tr>
<td>Back (Full)</td>
<td>Dental injury/broken tooth</td>
<td>Environmental</td>
</tr>
<tr>
<td>Cervical spine/Neck</td>
<td>Fracture (trauma, stress, other bone</td>
<td>Gastrointestinal</td>
</tr>
<tr>
<td>Elbow</td>
<td>injuries)</td>
<td>Immunological</td>
</tr>
<tr>
<td>Face (including eye, ear, nose)</td>
<td>Impingement</td>
<td>Metabolic</td>
</tr>
<tr>
<td>Finger</td>
<td>Laceration/abrasion/skin lesion</td>
<td>Other (including urogenital,</td>
</tr>
<tr>
<td>Forearm</td>
<td>Other (including nerve, spinal cord,</td>
<td>gynaecological,</td>
</tr>
<tr>
<td>Foot/toe</td>
<td>fasciitis</td>
<td>neurological,</td>
</tr>
<tr>
<td>Groin</td>
<td>Sprain (dislocation, subluxation,</td>
<td>psychiatric,</td>
</tr>
<tr>
<td>Head</td>
<td>ligamentous rupture)</td>
<td>neurological,</td>
</tr>
<tr>
<td>Hip</td>
<td>Strain (muscle rupture, tear, tendon</td>
<td>muscular,</td>
</tr>
<tr>
<td>Knee</td>
<td>rupture)</td>
<td>dental</td>
</tr>
<tr>
<td>Leg (Full)</td>
<td>Meniscus/cartilage</td>
<td>Respiratory</td>
</tr>
<tr>
<td>Leg (Lower)</td>
<td>Muscle cramps/spas</td>
<td></td>
</tr>
<tr>
<td>Lumbar spine/lower back</td>
<td>Patellofemoral pain syndrome</td>
<td></td>
</tr>
<tr>
<td>Organs</td>
<td>Postural</td>
<td></td>
</tr>
<tr>
<td>Patellofemoral joint</td>
<td>Tendinosis/tendinopathy</td>
<td></td>
</tr>
<tr>
<td>Pelvis/sacrum/buttock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder/clavicular</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sternum/ribs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoracic spine/upper back</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unknown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

or competition that following examination is diagnosed by a clinical professional as a medically recognized injury.”23

Overuse sports injury was defined as: “loss or abnormality of bodily structure or functioning resulting from repeated bouts of physical load without adequate recovery periods in association with sports training or competition that following examination is diagnosed by a clinical professional as a medically recognized disease or syndrome.”23 Illness was defined as “a physical or psychological complaint or manifestation by an athlete not related to injury, regardless of whether it received medical attention or its consequences with respect to impairments in connection with competition or training”.10,11 In addition to the categories of affected system as classified by the International Olympic Committee Injury Surveillance System, we also added a standalone category for cardiovascular and used symptom clusters to identify affected illness system based on the 2020 International Olympic Committee Consensus Statement (Table 1).24

STATISTICAL METHODS

Following data categorization, participants were separated male and female by sport to determine injury and illness frequency, incidence, and odds of injury and illness, with 95% confidence intervals, for male and female athletes across and between sports. Frequency of injury/illness types and locations were calculated as percentages. Injury/illness incidence was calculated as the total number of injuries/illnesses per 1000 registered athletes using registration numbers (numbers of athletes registered for competition per sport) provided by Canada Games Council. Incidence was calculated by first determining the total number of injuries/illnesses reported in all male and female athletes as well as separating out the total numbers of injuries/illnesses reported based on sport and sex. Once injury/illness totals were counted, the registration numbers were used to calculate incidence of injury in all athletes, male athletes, female athletes, and further subdivided to calculate incidence of injury in male or female athletes based on sport. Registration numbers were divided by 1000 to indicate the total number of participants per 1000. Consistent with previous research,12,13 incidence was then calculated as the total number of injuries/illnesses divided by the total number of athletes registered for competition in each sport (using the equation below).

\[
\text{Number of Injuries or Illnesses} = \frac{\text{Registration Number}}{1000}
\]

Odds ratios (from 2 x 2 contingency tables) were calculated to determine odds of injury/illness between male and female athletes and when comparing between similar sports. Additionally, 95% confidence intervals (95% CIs) were calculated to determine precision. Data were analyzed in Excel; the 95% CI (interval exclusion of null of 1.0) was used to indicate statistical significance in odds of injuries/illnesses between males and females competing in Canada Games. MedCalc (https://www.medcalc.org/; v.20.113) was used to determine statistically significant differences (p < 0.05) in incidence of injury/illness (overall and in Summer vs. Winter Games) between male and females athletes competing in Canada Games.
Table 2. Injury location for male and female participants across all 10 years of Canada Games competitions.

<table>
<thead>
<tr>
<th>Injury Location (n; % of total injuries)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdomen</td>
<td>17: 0.5%</td>
<td>15: 0.4%</td>
</tr>
<tr>
<td>Achilles Tendon</td>
<td>29: 0.9%</td>
<td>37: 1.1%</td>
</tr>
<tr>
<td>Ankle</td>
<td>243: 7.4%</td>
<td>232: 6.8%</td>
</tr>
<tr>
<td>Arm (Upper)</td>
<td>41: 1.2%</td>
<td>30: 0.9%</td>
</tr>
<tr>
<td>Back (Full)</td>
<td>21: 0.6%</td>
<td>18: 0.5%</td>
</tr>
<tr>
<td>Cervical Spine/Neck</td>
<td>156: 4.7%</td>
<td>228: 6.7%</td>
</tr>
<tr>
<td>Elbow</td>
<td>88: 2.7%</td>
<td>85: 2.5%</td>
</tr>
<tr>
<td>Face</td>
<td>93: 2.8%</td>
<td>61: 1.8%</td>
</tr>
<tr>
<td>Finger</td>
<td>91: 2.8%</td>
<td>60: 1.8%</td>
</tr>
<tr>
<td>Forearm</td>
<td>43: 1.3%</td>
<td>37: 1.1%</td>
</tr>
<tr>
<td>Foot/Toe</td>
<td>144: 4.4%</td>
<td>131: 3.8%</td>
</tr>
<tr>
<td>Groin</td>
<td>70: 2.1%</td>
<td>55: 1.6%</td>
</tr>
<tr>
<td>Head</td>
<td>43: 1.3%</td>
<td>32: 0.9%</td>
</tr>
<tr>
<td>Hip</td>
<td>112: 3.4%</td>
<td>96: 2.8%</td>
</tr>
<tr>
<td>Knee</td>
<td>128: 3.9%</td>
<td>125: 3.6%</td>
</tr>
<tr>
<td>Leg (Full)</td>
<td>215: 6.5%</td>
<td>288: 8.4%</td>
</tr>
<tr>
<td>Leg (Lower)</td>
<td>7: 0.2%</td>
<td>9: 0.3%</td>
</tr>
<tr>
<td>Lumbar Spine/Low Back</td>
<td>178: 5.4%</td>
<td>213: 6.2%</td>
</tr>
<tr>
<td>Organs</td>
<td>350: 10.6%</td>
<td>378: 11.0%</td>
</tr>
<tr>
<td>Patellofemoral Joint</td>
<td>6: 0.2%</td>
<td>0</td>
</tr>
<tr>
<td>Pelvis/Sacrum</td>
<td>163: 4.9%</td>
<td>188: 5.5%</td>
</tr>
<tr>
<td>Sternum/Ribs</td>
<td>61: 1.8%</td>
<td>87: 2.5%</td>
</tr>
<tr>
<td>Shoulder/Clavicle</td>
<td>373: 11.3%</td>
<td>405: 11.8%</td>
</tr>
<tr>
<td>Thoracic Spine/Upper Back</td>
<td>237: 7.2%</td>
<td>247: 7.2%</td>
</tr>
<tr>
<td>Thigh</td>
<td>302: 9.1%</td>
<td>234: 6.8%</td>
</tr>
<tr>
<td>Unknown</td>
<td>0</td>
<td>1: 0.03%</td>
</tr>
<tr>
<td>Wrist</td>
<td>52: 1.6%</td>
<td>68: 2.0%</td>
</tr>
</tbody>
</table>

Total number of athletes across all 10 years of Canada Games: 8710 male; 8391 female

RESULTS

Across all 10 years of Canada games, 3160 injuries reported in 8710 male athletes (n = 5457 in Summer Games; 3253 in Winter Games) and 3272 injuries reported in 8391 female athletes (n = 4712 in Summer Games; 3679 in Winter Games). Injury incidence was 362.8 and 389.9 (p = 0.004) and illness incidence was 47.8 and 64.5 (p < 0.001) per 1000 male and female athletes, respectively. Injuries to the shoulder (Table 2) and muscle strains (Table 3) were the most common regardless of sex.

The respiratory system was most often affected illness system for male and female athletes (Table 4). Female, compared to male, athletes had a 1.12 (95% CI: 1.06; 1.19) significantly greater odds of injury and 1.37 (95% CI: 1.20; 1.57) significantly greater odds of illness.

Assessing Summer and Winter Canada Games competitions separately, the overall injury and illness incidences were significantly higher in Winter, compared to Summer, Canada Games when all athletes were combined and in male athletes (Figure 1). Overall incidence of illness was significantly higher in females competing in Winter compared to Summer Games; however, there was no difference in overall incidence of injuries in females competing in Winter compared to Summer Games (Figure 1).

Female freestyle skiing participants had the highest injury incidence while female target shooting participants had the highest illness incidence (Tables 5 and 6). Female athletes competing in softball, canoe-kayak, rowing, sailing, swimming, tennis, triathlon, fencing, alpine skiing, biathlon, judo, snowboarding, and wheelchair basketball had a significantly increased odds of injury compared to males competing in similar sports (Tables 5 and 6). Female athletes competing in athletics, softball, soccer, and speed skating had a significantly increased odds of illness compared to males competing in similar sports; while females competing in diving had a significantly decreased odds of illness compared to male participants (Tables 5 and 6).

Injuries were most common across all athletes in Summer and Winter games (Table 7); thigh and shoulder were the most frequently injured in male Summer and Winter participants, respectively; shoulder was most frequent in female Summer and Winter participants (Table 7). Male Summer and Winter participants reported more acute injuries; female Summer and Winter participants reported more chronic injuries (Table 7). In Summer Games, participants reported highest illness in other category (urogenital, gynaecological, neurological, psychiatric) (Table 7) and in Winter games respiratory system was most often affected system for illness (Table 7).

DISCUSSION

The purpose of this study was to analyze the incidence and characteristics of injuries and illnesses during Canada Games competitions from 2009–2019 and to understand sex differences in odds of musculoskeletal injury for Summer and Winter Canada Games athletes. The Canada Games occur every two years and alternate between Summer and Winter Games. Overall, there were similarities in types of injuries and illnesses as well as area of the body commonly injured, however; incidence and odds of injury and illness differed between male and female athletes.

INJURY TYPES, INVOLVED BODY AREAS, AND AFFECTED SYSTEMS

When considering all 10 years of Canada Games competitions, strains, sprains, and contusions/haematomas/bruises were most common; demonstrating that approximately 70% of all injuries during 10 years of Canada Games competitions were of one of three injury type categories. These findings are similar to those reported in the 2008 and 2010 Olympic Games with contusions (26 – 46%), sprains (11 – 20%), and strains (8 – 16%) being most common.12,13,25
Previous findings suggest that male athletes sustained significantly more injuries to the thigh region (Relative Risk [RR] = 1.64; 95% CI 1.32; 2.05) with a 1.66 (95% CI 1.25; 2.19) increased risk of thigh strains compared to female participants during International Athletics Competitions.\textsuperscript{16} Although the measure of RR is different from the odds ratios presented in this current study, both measures are used to describe an association between a variable and an outcome. However, there are distinct differences between measuring RR and OR. Relative risk assesses the probability of an injury occurring and requires participants at risk to consider the frequency of a risk while OR primarily consider the rate of injury.\textsuperscript{26,27} In a retrospective design, which was used in this current study, because the total number of participants at risk is not known, RR cannot be calculated. Therefore, OR were used in this current study to measure the strength of association between variables (males and females or Summer and Winter Games) and the outcomes of interest (injury types, locations, etc.).

When considering male and female participants across all 10 years of Canada Games competitions, in addition to the shoulder and thigh, the ankle and knee were the also commonly injured body areas. These findings are more consistent with previous literature suggesting that lower extremity injuries occur most commonly (at least half of all injuries) as reported in previous Olympic competitions,\textsuperscript{12,13,25} in Olympic athletes on the British World Class Performance Programme,\textsuperscript{28} and Youth Olympic Games.\textsuperscript{29} Additionally, across all 10 years of Canada Games competitions as well as when comparing specifically between Summer and Winter Canada Games, males had more acute injuries while females had more chronic injuries. These findings are directly in line with previous reports from a Division I collegiate institution in the United States indicating female athletes had a greater rate of chronic injuries per 10000 athlete exposures (AEs) across three years of competition while males athletes had a higher rate of acute injuries per 10000 AEs in the same time frame.\textsuperscript{18} Perhaps these combined findings suggest a need to investigate mitigating risk of injury differently between male and female athletes with greater focus on prevention of chronic injury in female and acute injury in males.

Across all 10 years of Canada Games competitions, the respiratory system was the most often affected system in illness while the category of ‘other’ was the second most affected system. Together these two systems represented more than 50% of all illness in both male and female participants. This is consistent with previous literature indicating the respiratory system was the most commonly reported system affected (19 - 62% of all reported illnesses) in Summer and Winter Olympics, International Athletics Competitions, Rugby, and Youth Olympic Games.\textsuperscript{11,12,19,29–31} Risk factors for respiratory illness can include stress (mechanical/dehydration) to the airway as well as airborne pollutants, irritants, and allergens that can be inhaled by the athlete during exercise.\textsuperscript{32} Given the demands of sport there are inherent stresses to the respiratory system that may be further exacerbated by air quality, which cannot be prevented.

### Table 3. Injury type for male and female participants across all 10 years of Canada Games competitions

<table>
<thead>
<tr>
<th>Injury Type (n; % of total injury types)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arthritis/Synovitis/Bursitis</td>
<td>21; 0.7%</td>
<td>34; 1.0%</td>
</tr>
<tr>
<td>Compartment Syndrome</td>
<td>5; 0.2%</td>
<td>9; 0.3%</td>
</tr>
<tr>
<td>Concussion</td>
<td>80; 2.5%</td>
<td>74; 2.3%</td>
</tr>
<tr>
<td>Contusion/Hematoma/Bruise</td>
<td>386; 12.2%</td>
<td>299; 9.1%</td>
</tr>
<tr>
<td>Dental/Tooth</td>
<td>3; 0.1%</td>
<td>3; 0.1%</td>
</tr>
<tr>
<td>Fracture</td>
<td>110; 3.5%</td>
<td>107; 3.3%</td>
</tr>
<tr>
<td>Impingement</td>
<td>40; 1.3%</td>
<td>56; 1.7%</td>
</tr>
<tr>
<td>Laceration/Abrasion/Skin</td>
<td>228; 7.2%</td>
<td>173; 5.3%</td>
</tr>
<tr>
<td>Meniscus/Cartilage</td>
<td>32; 1.0%</td>
<td>51; 1.6%</td>
</tr>
<tr>
<td>Muscle Cramp/Spasm</td>
<td>139; 4.4%</td>
<td>143; 4.4%</td>
</tr>
<tr>
<td>Other</td>
<td>51; 1.6%</td>
<td>64; 2.0%</td>
</tr>
<tr>
<td>Patellofemoral Pain Syndrome</td>
<td>35; 1.1%</td>
<td>61; 1.9%</td>
</tr>
<tr>
<td>Postural</td>
<td>9; 0.3%</td>
<td>12; 0.4%</td>
</tr>
<tr>
<td>Sprain</td>
<td>674; 21.3%</td>
<td>770; 23.5%</td>
</tr>
<tr>
<td>Strain</td>
<td>1149; 36.4%</td>
<td>1236; 37.8%</td>
</tr>
<tr>
<td>Tendinopathy</td>
<td>198; 6.3%</td>
<td>180; 5.5%</td>
</tr>
<tr>
<td>Acute</td>
<td>1716; 54.3%</td>
<td>1534; 46.9%</td>
</tr>
<tr>
<td>Chronic</td>
<td>1444; 45.7%</td>
<td>1738; 53.1%</td>
</tr>
</tbody>
</table>

Total number of athletes across all 10 years of Canada Games: 8710 male; 8591 female

### Table 4. Affected system (illness) for male and female participants across 10 years of Canada Games competitions

<table>
<thead>
<tr>
<th>Affected System (n; % of total illnesses)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allergic</td>
<td>6; 1.4%</td>
<td>24; 4.4%</td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>14; 3.4%</td>
<td>14; 2.6%</td>
</tr>
<tr>
<td>Dermatologic</td>
<td>63; 15.1%</td>
<td>61; 11.3%</td>
</tr>
<tr>
<td>Endocrinological</td>
<td>0</td>
<td>2; 0.4%</td>
</tr>
<tr>
<td>Environmental</td>
<td>18; 4.3%</td>
<td>19; 3.5%</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>70; 16.8%</td>
<td>76; 14.0%</td>
</tr>
<tr>
<td>Immunological</td>
<td>0</td>
<td>1; 0.2%</td>
</tr>
<tr>
<td>Metabolic</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>114; 27.4%</td>
<td>153; 28.3%</td>
</tr>
<tr>
<td>Respiratory</td>
<td>131; 31.5%</td>
<td>191; 35.3%</td>
</tr>
</tbody>
</table>

Total number of athletes across all 10 years of Canada Games: 8710 male; 8591 female

Overall, the shoulder was the most commonly injured body area in all participants. However, when considering injured body area in male and female participants in Summer and Winter Canada Games separately, the thigh was most commonly injured in male participants in Summer Games.
Injuries and Illnesses Across 10 Years of Canada Games Competitions: 2009 – 2019

Figure 1. Injury and Illness Incidence per 1000 athletes in Summer and Winter Canada Games.

Incidence was calculated by first determining the total number of injuries in all athletes, in male athletes, and in female athletes for both Winter and Summer Games. The number of registered athletes (based on the categories of total, male, female, winter, and summer) were divided by 1000 and used as the denominator whereby total number of injuries/illnesses were divided by.

* Significant difference in Winter compared to Summer Games for total and male injury incidence and total, male, and female illness incidence; p < 0.001

† Significant difference in Winter compared to Summer Games for female illness incidence; p = 0.004

INCIDENCE AND ODDS OF INJURY AND ILLNESS

Injury incidence was higher in female, compared to male, athletes across all 10 years of Canada Games competitions. When considering differences specific to participation in Summer versus Winter Canada Games, incidence of injury was higher in Winter than Summer Games across all athletes. When looking at participation in specific sports, female athletes had a higher incidence of injury, per 1000 athletes, in the majority of Summer and Winter Canada Games sports. Interestingly, incidence of injury was nearly identical between in females competing in Summer and Winter Games, while males competing in Winter Games had higher incidence of injury than males competing in Summer Games. This may suggest more consistency in female athlete’s reporting of injury across all Games.

Similar to injury incidence reports from the 2008 Summer Olympic Games, the lowest overall incidence of injury per 1000 Summer Canada Games participants in swimming, canoe-kayak, and sailing. In Winter Canada Games, the highest overall incidence of injury per 1000 athletes was observed in freestyle skiing and women’s snowboarding. These findings are similar to those reported from the 2010 and 2014 Winter Olympic Games with alpine skiing and snowboarding having high injury risk and injury incidence. Additionally, similar to the current findings, incidence of injury (per 1000 athletes) was lowest in men’s archery, previous research suggests low injury rates or incidences in archery and table tennis during Olympic competition. Collectively, these Canada Games injury incidence findings are in support of suggestions that sports with jumping, cutting, sprinting, and pivoting have higher risk of injury.

Female athletes had a significantly increased odds of injury when combining all athletes together; however, odds of injury varied when also considering specific sport participation. In Canada Winter Games, female alpine skiers had a 2.6 greater odds of injury compared to male alpine skiers.
Table 5. Summer Games Injury and Illness Incidence per 1000 athletes per sport

<table>
<thead>
<tr>
<th>Sport</th>
<th>Male</th>
<th>Female</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injury Incidence OR [95% CI]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Athletics</td>
<td>824:♂  ♀  796</td>
<td>349.1</td>
<td>355.7</td>
<td>10.0 [0.8;1.3]</td>
</tr>
<tr>
<td>Baseball/Softball</td>
<td>586:♂  ♀  448</td>
<td>188.9</td>
<td>472.3</td>
<td>3.8 [2.9;5.1]</td>
</tr>
<tr>
<td>Basketball</td>
<td>416:♂  ♀  384</td>
<td>448.1</td>
<td>414.9</td>
<td>0.9 [0.7;1.2]</td>
</tr>
<tr>
<td>Canoe-Kayak</td>
<td>229:♂  ♀  217</td>
<td>153.7</td>
<td>301.7</td>
<td>2.4 [1.5;3.8]</td>
</tr>
<tr>
<td>Cycling</td>
<td>209:♂  ♀  143</td>
<td>291.2</td>
<td>330.1</td>
<td>1.2 [0.8;1.9]</td>
</tr>
<tr>
<td>Diving</td>
<td>93:♂  ♀  86</td>
<td>441.8</td>
<td>336.6</td>
<td>0.6 [0.3;1.1]</td>
</tr>
<tr>
<td>Golf</td>
<td>102:♂  ♀  91</td>
<td>234.8</td>
<td>260.6</td>
<td>1.2 [0.6;2.2]</td>
</tr>
<tr>
<td>Fencing*</td>
<td>53:♂  ♀  42</td>
<td>301.9</td>
<td>904.8</td>
<td>22.0 [6.7;71.9]</td>
</tr>
<tr>
<td>Rowing</td>
<td>326:♂  ♀  337</td>
<td>177.6</td>
<td>329.6</td>
<td>2.2 [1.5;3.2]</td>
</tr>
<tr>
<td>Rugby*</td>
<td>250:♂  ♀  0</td>
<td>728.0</td>
<td>N/A</td>
<td>60.0</td>
</tr>
<tr>
<td>Sailing</td>
<td>90:♂  ♀  91</td>
<td>164.8</td>
<td>529.9</td>
<td>5.6 [2.8;11.1]</td>
</tr>
<tr>
<td>Soccer</td>
<td>642:♂  ♀  620</td>
<td>523.0</td>
<td>433.0</td>
<td>0.7 [0.6;0.9]</td>
</tr>
<tr>
<td>Swimming</td>
<td>483:♂  ♀  493</td>
<td>89.0</td>
<td>144.8</td>
<td>1.7 [1.2;2.6]</td>
</tr>
<tr>
<td>Tennis</td>
<td>129:♂  ♀  125</td>
<td>344.8</td>
<td>554.1</td>
<td>2.3 [1.4;3.8]</td>
</tr>
<tr>
<td>Triathlon</td>
<td>89:♂  ♀  89</td>
<td>271.8</td>
<td>581.9</td>
<td>3.8 [2.0;7.1]</td>
</tr>
<tr>
<td>Volleyball</td>
<td>470:♂  ♀  472</td>
<td>353.8</td>
<td>412.4</td>
<td>1.3 [1.0;1.7]</td>
</tr>
<tr>
<td>Wrestling</td>
<td>317:♂  ♀  278</td>
<td>537.7</td>
<td>495.4</td>
<td>0.8 [0.6;1.2]</td>
</tr>
<tr>
<td><strong>Illness Incidence OR [95% CI]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>0.5 [0.3;3.0]</td>
<td>50.0</td>
<td>20.0</td>
<td>3.1 [0.6;16.3]</td>
</tr>
<tr>
<td>Female</td>
<td>4.0 [1.0;15.0]</td>
<td>120.0</td>
<td>60.0</td>
<td>4.6 [0.9;22.4]</td>
</tr>
</tbody>
</table>

OR = odds ratio for odds of injury or illness if female compared to male athlete competing in similar sport. N/A = odds of injury/illness not calculated based on no participants or injuries/illnesses being recorded in male or female participants. OR were calculated from 2 x 2 contingency tables with 95% CI calculated for precision and statistical significance. Total number of male and female athletes registered for competition per sport are indicated under each sport in the sport column. *data are from one year of competition only due to change in sport inclusion in Canada Games.

There are limited reports of differences in odds of injury between male and female athletes competing in high levels of competition; one study reported findings similar to ours suggesting that female athletes competing in slopestyle skiing were at greater risk of injury compared to male athletes (RR=5.00; 95% CI: 1.04; 8.63). Additionally, female fencers had 22 times greater odds of injury compared to their male counterparts. It has been previously reported that male fencers have higher relative risk (RR=1.42, 95% CI 1.05 to 1.94) of time loss injury compared to female fencers; perhaps the difference in our findings from those previously reported are that we included all injuries rather than only those that resulted in time loss. It has been suggested that as much as 90% of overuse injuries may be missed when using time loss in defining injury. The normalization of continuing to participate at all costs, even when injured, can limit the understanding of injury epidemiology in large scale events such as Canada Games if injury definitions only include time loss injuries. Further, injuries sustained in sport can impact both preparation for, and performance in, future sport participation. Therefore, previous literature has advocated for the use of more inclusive injury definitions.

Similar to injury incidence, illness incidence was higher in female, compared to male, athletes across all 10 years of Canada Games competitions. This is similar to the reports that women competing in the 2010 Vancouver, 2012 London, and 2014 Sochi Olympics had higher reports of illnesses compared to male athletes. Previous literature has indicated female athletes had 1.5 times greater
relative risk for developing an illness compared to male athletes.\(^3\) When considering differences specific to participation in Summer versus Winter Canada Games, incidence of illness was higher in Winter than Summer Games. This may not be surprising given that exposure to cold during winter months increases the risk of developing respiratory illness, which may be due to vasoconstriction in the respiratory tract mucosa and suppression of immune responses that occur with inhaling cold air.\(^3\)

It is important to acknowledge that boxing and rugby had only male participants while synchronized swimming and ringette had only female participants. Both fencing and golf had no illnesses reported by male participants during any years of Canada Games so a comparison could not be directly assessed between male and female illness incidence or odds; to the researcher's knowledge this does not represent an error in reporting but rather a lack of illness being reported by any member of these teams. Further, rugby and fencing were only included in Canada Games competitions in only 2009 and 2013 respectively; therefore, for each of these sports, only one year of data are available. Finally, exposure and time loss data were not collected, therefore in-

<table>
<thead>
<tr>
<th></th>
<th>Injury Incidence OR [95% CI]</th>
<th>Illness Incidence OR [95% CI]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Alpine Skiing ♂ = 200; ♂ = 186</td>
<td>267.5</td>
<td>460.9 [2.3[1.5;3.5]]</td>
</tr>
<tr>
<td>Archery ♂ = 59; ♂ = 59</td>
<td>139.2</td>
<td>188.3 [1.5[0.5;3.9]]</td>
</tr>
<tr>
<td>Badminton ♂ = 172; ♂ = 163</td>
<td>548.2</td>
<td>456.4 [0.7[0.4;1.1]]</td>
</tr>
<tr>
<td>Biathlon ♂ = 120; ♂ = 119</td>
<td>356.8</td>
<td>633.3 [3.1[1.8;5.2]]</td>
</tr>
<tr>
<td>Boxing ♂ = 108; ♂ = 0</td>
<td>646.7</td>
<td>N/A</td>
</tr>
<tr>
<td>Cross Country Skiing ♂ = 193; ♂ = 182</td>
<td>247.6</td>
<td>330.1 [1.5[0.9;2.3]]</td>
</tr>
<tr>
<td>Curling ♂ = 140; ♂ = 143</td>
<td>198.9</td>
<td>252.2 [1.4[0.8;2.4]]</td>
</tr>
<tr>
<td>Figure Skating ♂ = 130; ♂ = 191</td>
<td>197.0</td>
<td>141.9 [0.7[0.4;1.2]]</td>
</tr>
<tr>
<td>Freestyle Skiing ♂ = 107; ♂ = 72</td>
<td>774.2</td>
<td>1015.2 [N/A]</td>
</tr>
<tr>
<td>Gymnastics ♂ = 211; ♂ = 235</td>
<td>717.4</td>
<td>539.0 [0.5[0.3;0.7]]</td>
</tr>
<tr>
<td>Ice Hockey ♂ = 741; ♂ = 697</td>
<td>337.2</td>
<td>310.2 [0.9[0.7;1.1]]</td>
</tr>
<tr>
<td>Judo ♂ = 198; ♂ = 167</td>
<td>464.2</td>
<td>621.5 [1.8[1.2;2.8]]</td>
</tr>
<tr>
<td>Ringette ♂ = 0; ♂ = 468</td>
<td>N/A</td>
<td>439.8 [N/A]</td>
</tr>
<tr>
<td>Snowboarding ♂ = 134; ♂ = 107</td>
<td>524.7</td>
<td>732.7 [2.6[1.5;4.5]]</td>
</tr>
<tr>
<td>Speed Skating ♂ = 246; ♂ = 231</td>
<td>417.5</td>
<td>356.6 [0.8[0.5;1.1]]</td>
</tr>
<tr>
<td>Squash ♂ = 136; ♂ = 130</td>
<td>490.3</td>
<td>473.0 [0.9[0.6;1.5]]</td>
</tr>
<tr>
<td>Synchronized Swimming ♂ = 0; ♂ = 288</td>
<td>N/A</td>
<td>205.6 [N/A]</td>
</tr>
<tr>
<td>Table Tennis ♂ = 101; ♂ = 94</td>
<td>174.0</td>
<td>175.9 [0.9[0.5;2.0]]</td>
</tr>
<tr>
<td>Target Shooting ♂ = 70; ♂ = 74</td>
<td>262.3</td>
<td>373.6 [1.8[0.9;3.6]]</td>
</tr>
<tr>
<td>Wheelchair Basketball ♂ = 187; ♂ = 73</td>
<td>607.7</td>
<td>888.4 [4.1[2.2;7.7]]</td>
</tr>
</tbody>
</table>

OR = odds ratio for injury or illness if female compared to male athlete competing in similar sport. N/A = odds of injury/illness not calculated based on no participants or injuries/illnesses being recorded in male or female participants. OR were calculated from 2 x 2 contingency tables with 95% CIs calculated for precision and statistical significance.
Table 7. Most common injury type, body area, chronic/acute, affected system (illness) in male and female athletes across 10 years of Summer and Winter Canada Games

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injury Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain</td>
<td>n = 603 (32.5%)</td>
<td>n = 616 (34.0%)</td>
<td>n = 546 (41.8%)</td>
<td>n = 620 (42.4%)</td>
</tr>
<tr>
<td><strong>Body Area</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td>n = 215 (11.0%)</td>
<td>Shoulder</td>
<td>n = 192 (14.3%)</td>
<td>Shoulder</td>
</tr>
<tr>
<td>n = 204 (10.8%)</td>
<td>n = 175 (10.2%)</td>
<td>n = 204 (10.8%)</td>
<td>n = 200 (13.0%)</td>
<td></td>
</tr>
<tr>
<td><strong>Chronic/Acute</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acute</td>
<td>n = 1019 (55.0%)</td>
<td>Chronic</td>
<td>n = 697 (33.4%)</td>
<td>Chronic</td>
</tr>
<tr>
<td>n = 975 (53.9%)</td>
<td>n = 336 (17.9%)</td>
<td>n = 763 (52.2%)</td>
<td>n = 763 (52.2%)</td>
<td></td>
</tr>
<tr>
<td><strong>Affected System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>n = 69 (31.7%)</td>
<td>Other</td>
<td>n = 73 (27.8%)</td>
<td>Respiratory</td>
</tr>
<tr>
<td>n = 73 (27.8%)</td>
<td>n = 46 (11.9%)</td>
<td>Respiratory</td>
<td>n = 85 (42.9%)</td>
<td>Respiratory</td>
</tr>
<tr>
<td>n = 131 (47.1%)</td>
<td>n = 46 (11.9%)</td>
<td>n = 131 (47.1%)</td>
<td>n = 131 (47.1%)</td>
<td></td>
</tr>
</tbody>
</table>

Incidence rate cannot be calculated, and the incidence of injury/illness data cannot be dichotomized into time loss vs. no time loss. To give a frame of reference to the number of injuries/illnesses, we used athlete registration numbers to report incidence per 1000 athletes registered for competition. These are limitations to the data set as well as the retrospective design of the secondary analysis of data; however, this is the first report of the epidemiology of injury and illness during Canada Games and therefore provides an understanding to the differences that exist in male and female athletes competing in Canada Games competitions.

CONCLUSION

Although injured body area and type of injury were similar between males and females competing in Canada Games, female athletes had a significantly greater overall odds of both injury and illness. Differences exist in injuries and illnesses between Summer and Winter Canada Games and between male and female participants in like sports. Given these differences, there may be an interest in future exploration of modifiable risk factors as this may help to clinicians to target strategies to reduce injuries that occur during Canada Games competitions.

CONFLICT OF INTEREST DISCLOSURE

Chimera – Brock University Canada Games Grant provided support for hiring a research assistant and for conference registration fees

Merasty – paid research assistant through Chimera’s Brock University Canada Games Grant funding

Lininger - none

ACKNOWLEDGEMENTS

The authors wish to thank and Canada Games Council for providing de-identified data for this analysis. This work was supported by a Brock University Canada Games Grant.

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International Journal of Sports Physical Therapy
REFERENCES


Original Research

Influence of High School Socioeconomic Status on Athlete Injuries during the COVID-19 Pandemic: An Ecological Study

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Keywords: Household Income, Collision Sport, Incidence, Socio-determinants of Health

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Background

It is presently unclear how the cessation of high school sport has affected injury incidence at different socioeconomic levels. The COVID-19 pandemic may have disproportionately affected athletes of lower socioeconomic status, potentially increasing injury risk in this population.

Purpose

To 1) Describe athlete injury incidence prior to and during the 2019-2020 and 2020-2021 school years in high school athletes by socioeconomic status; 2) Investigate the association between socioeconomic status and injury incidence in high school athletes.

Study Design

Ecological Study

Methods

High schools were matched between the 2019-2020 and 2020-2021 school years. All athletes from all sports were included. High school socioeconomic status was determined by the school district median household income. Socioeconomic strata were defined as <$30,000, $30,000-50,000, $50,001-100,000, and >$100,000. Injury incidence proportion with 95% confidence interval (95% CI) was calculated for each academic year. Mixed effects negative binomial models with robust errors were performed to assess the association between the incidence proportion ratio and high school median household income. Six states and 176 high schools were included (2019-2020: 98,487 athletes; 2020-2021: 72,521 athletes).

Results

Injury incidence increased in three of four socioeconomic strata during the 2020-2021 year (<$30,000: 2019-2020: 15.6 (13.1-18.1), 2020-2021: 26.3 (23.1-29.6); $30,000-50,000: 2019-2020: 7.8 (7.1-8.6), 2020-2021: 14.9 (13.8-15.9); $50,001-100,000: 2019-2020: 15.1 (14.7-15.4), 2020-2021: 21.3 (20.9-21.8); >$100,000: 2019-2020: 18.4 (18.1-18.8), 2020-2021: 17.3 (16.8-17.7)). An association was observed between injury incidence ratio and log median high school household income in 2019-2020 [1.6 (1.1-2.5)] but not 2020-2021 [1.1 (0.8-1.6)] school years.

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Conclusions
Athletes from lower socioeconomic high schools reported increased injury incidence compared to higher socioeconomic high schools during the 2020-2021 academic school year. These results highlight the increased COVID-19 pandemic vulnerability in athletes from lower socioeconomic high schools. High school sport stakeholders should consider how abrupt sport stoppage can affect lower socioeconomic athletes.

Level of Evidence
2

INTRODUCTION
There are over 15 million high school students in the United States, with over eight million participating in high school sports yearly.1,2 High school sports play a pivotal role in student health and wellbeing, including cardiovascular fitness,3,4 psychological wellbeing,5,6 academic performance,7–9 and quality of life.10–12 However, participating in high school sport poses inherent risk. High school athletes suffer an estimated 1.4 million injuries per year and sustain as high as 4.6 injuries and 0.7 severe injuries per 1000 athletes exposures.13,14 These injuries result in 2.5 million high school athletes eliciting emergency department services,15 and costing $44.7 million in human capital and $144.6 million in comprehensive costs annually as reported in 2007.16

Abrupt cessation of practice and game play can increase injury risk in high school athletes.17,18 This increased injury risk is related to decreased cardiovascular fitness and conditioning, reductions in strength, and decreased sport specific training.18–20 During the spring and summer of 2020, the SARS-CoV-2 coronavirus and the resultant disease, coronavirus disease (COVID-19) pandemic stemmed an abrupt stoppage of high school sport training, practice, and competition.21,22 The prolonged cessation from high school training and sport resulted in overall decreases in physical activity, running, and individual sport specific practice.23–26 The return to high school sport during the subsequent academic school year may have exposed high school athletes to abrupt increases in training and competition load,18–20 predisposing these athletes to increased injury incidence and subsequent medical burden.24,25

There is a distinct relationship between an individual’s living environment and physical activity.27 Availability and access to parks, running trails, and sport and recreational facilities have demonstrated improved physical activity habits, sport participation, and overall physical health in adolescents and adults.28–31 However, socioeconomic status can influence access to recreational and park facilities, with cost, safety, weather, and quality and density of recreational facilities identified as potential barriers.28,32–34 Individuals and families of lower socioeconomic status have also demonstrated decreased physical activity habits, irrespective of race or urban or rural settings.35,36 Further, high school athletes from lower socioeconomic levels reported decreased weekly organized practice hours and months training compared to higher socioeconomic level athletes.37 During the COVID-19 pandemic, people of lower socioeconomic status were disproportionally affected by infection prevalence38 and less healthcare resources.39 High school athletes of lower socioeconomic may also have been disproportionately affected.26 In a survey of 13,000 high school athletes, male and female athletes from lower socioeconomic backgrounds reported decreased physical activity and higher anxiety and depression compared to athletes of higher socioeconomic status.26 This highlights a clinical and research gap concerning the current understanding of the impact of socioeconomic status on athlete injury risk when returning to sport following high school sport cessation.

It is presently unclear how the cessation of high school practice and game play has affected injury incidence in adolescent athletes. Socioeconomic status can influence physical activity,35,36 and recreational and leisure resources.28,32–34 Further, the COVID-19 pandemic may have disproportionately affected athletes of lower socioeconomic status,26,38,39 potentially increasing injury risk in this population. These data can inform sports medicine clinicians, educators, and policy makers on understanding the secondary effects of the COVID-19 pandemic, specifically high school injury burden at different socioeconomic strata. Therefore, the purpose of this study was to 1) Describe athlete injury incidence prior to and during the 2019-2020 and 2020-2021 school years in high school athletes by socioeconomic status; 2) Investigate the association between socioeconomic status and injury incidence in high school athletes.

METHODS
STUDY DESIGN
An ecological study investigating the influence of high school socioeconomic status on athlete injury incidence over an academic year was performed, with the high school level used as the unit of analyses. The Strengthening the Reporting of Observational Studies in Epidemiology for Sport Injury and Illness Surveillance (STROBE-SIIS) were followed.40 Informed consent was not required as this was a retrospective study. This investigation was approved by the University Institutional Review Board.

DATA COLLECTION
Athletes presenting with any illness or injury reported to their school athletic trainer (AT) and were documented as presenting with a time-loss problem during a team-sponsored practice or game. AT sport coverage was based on the school’s sport participation population, not on socioeco-
Influence of High School Socioeconomic Status on Athlete Injuries during the COVID-19 Pandemic: An Ecological Study

nomic status. Internal validity data checks were performed by the regional athletic trainer supervisor and the regional and national quality control supervisors on a quarterly basis.

PARTICIPANTS

High school athletes, from six states (Alabama (AL); Delaware (DE); Illinois (IL); Maryland (MD); Michigan (MI); Pennsylvania (PA)) were included in this study. High schools were matched between the 2019-2020 and 2020-2021 academic school years. Matching was based on the high school participating in athletics during the 2020-2021 academic school year. If the high school did not report or participate in high school athletics during the 2020-2021 year, they were excluded from the analyses (Figure 1). This resulted in 176 high schools rostered in the Players Health Rehab System for participating sports over the two-year study. Athlete health was monitored by the full-time athletic trainer assigned to each school by ATI Physical Therapy.

EXPOSURE DEFINITION

The main exposure was year of the pandemic, defined as athlete participation training, practices, or games on academic year 2020-2021. An athlete-exposure (AE) was defined as one athlete participating in one practice or competition where a player was at risk of sustaining an injury.\textsuperscript{41,42}

OUTCOME

An injury was defined as tissue damage or other derangement of normal physical function occurring during any training session or competition that resulted in at least one day lost to training and/or competition and that required medical attention.\textsuperscript{40,43} Athlete complaints that resulted in cessation of a competition or training session but the athlete returned to training or competition the same session or the following day were recorded as zero days of time loss and did not result in a recorded injury.\textsuperscript{40} Injured body segments and body parts were defined by the Orchard Sports Injury Classification System.\textsuperscript{44} Injury severity calculated as overall time loss, with further injury severity stratified by 7-28 (moderate) and 28+ (severe) days.\textsuperscript{40} The AT documented the injury or illness in the Players Health Rehab system. The documentation included the injury or illness date, athlete sex, sport of participation, body part, problem type, the participation status of the athlete, athlete phase of recovery and days until return to sport. Total data missingness was 5\%, for a more complete description of missingness, please refer to the statistical analyses section.

EXPLANATORY VARIABLE

High school socioeconomic status was determined by the median household income for the school district. Median household income was determined through federal public reports on National Center for Education Statistics. For epidemiological calculations, median household income was stratified into <$50,000, $50,000 to $50,001, $50,001 to $100,000, and >$100,000 based on previous public health research.\textsuperscript{45}

CONFOUNDERS

Self-identified gender, state, and sport were identified as confounders. Due to the large number of sports played, sport was collapsed into four categories: collision (American football, lacrosse, wrestling, ice hockey, rugby), field

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flowchart.png}
\caption{Participant Flow Chart}
\end{figure}
and court (basketball, field hockey, soccer, tennis, volleyball, gymnastics, softball, baseball), individual (track and field, swimming, mixed rifle, mixed skiing, golf, dance, diving, cross country, bowling, archery, rowing, cheerleading), and other. These sport collapsed categories are also alternatively known as collision, contact, and non-contact sports. Other was used for non-descript sport records.

STATISTICAL ANALYSES

All data were assessed for missingness prior to analyses (Gender: 0%; Age: 0%; Date of Injury: 3%; Sport: 1.7%; Body Part: 1.6%; Return to Play: <0.1%; Pain: <0.1%) with data demonstrating minimal missingness. Complete case analyses were performed. Participant statistics were described using mean (standard deviation) for continuous normally distributed variables, median (25th quartile, 75th quartile) for non-normally distributed continuous variables, and frequencies and percentages for categorical variables. Distributions were assessed through visual inspection and normal plots. Injury incidence proportion (also known as cumulative incidence) with 95% confidence interval (95% CI) was calculated as new injuries per 100 athletes for each academic year, overall and by state, gender, severity, sport, and body part.46 A mixed effects negative binomial model with robust errors were performed to assess the association between the incidence proportion ratio and high school median household income. Random effects were modeled at the high school level. Model fixed effects were controlled for gender, state, and percentage of male and female high school athletes compared to male and female school population. An offset of the log of male and female high school athlete participation was included. Due to the changes in injury incidence between the academic school years, academic school years were stratified. Sensitivity analyses included: 1) Including only severe injuries; 2) Including socioeconomic status as an ordinal variable, with $50,000 to $100,000 set as the reference; 3) Stratified by state. All analyses were performed in R version 4.01 (R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/), using the naniar package for missingness assessment47 and the GLMMadaptive package for mixed effects negative binomial modeling.48

RESULTS

A total of 98,487 athletes (Female: 43,250; Male: 55,239) participated in high school sport in the pre-pandemic academic year and 72,521 athletes (Female: 32,968; Male: 39,554) in the pandemic academic year. The median high school family income was $92,143 ($70,596, $115,692) with a range of $25,500 to $193,100. A total of three (2%) high schools reported a median high school family income of <$30,000, 10 (6%) $30,000 to $50,000, 99 (57%) $50,001 to $100,000, and 61 (35%) > $100,000.

A total of 15,477 injuries were reported in the pre-pandemic academic year compared to 14,057 injuries during the pandemic academic year. Median injury time loss stratified by socioeconomic status is reported in Table 1. For injury incidence stratified by socioeconomic status, gender, severity, sport, and state, please refer to Table 2, Table 3, and Table 4.

ASSOCIATION OF INJURY INCIDENCE RATIO AND HIGH SCHOOL SOCIOECONOMIC STATUS

Unadjusted [2.3 (95% CI: 1.4, 3.7)] and adjusted [1.6 (95% CI: 1.1, 2.5)] injury incidence increased for every unit of log median high school household income in the 2019–2020 academic year. Unadjusted injury incidence decreased by a ratio of 0.7 (95% CI: 0.5, 1.0) for every increase of log median high school household income in the 2020–2021 academic school year. Adjusted injury incidence demonstrated no association between injury incidence ratio of 1.1 (95% CI: 0.8, 1.6) log median high school household income in the 2020–2021 academic school year. For full models refer to Appendix A. For results of actual and predicted injury counts, please refer to Table 4.

SENSITIVITY ANALYSES

No relationship was observed between severe injury incidence and log median high school household income for the 2019–2020 academic school year 1.1 (95% CI: 0.8, 1.6) nor the 2020–2021 academic school year 0.7 (95% CI: 0.5, 1.0). Moderate injury incidence increased by a ratio of 1.6 (95% CI: 1.1, 2.4) for an increase of log median high school household income in the 2019–2020 academic school year. No relationship was observed between moderate injury incidence and log median high school household income for the 2020–2021 academic school year [1.1 (95% CI: 0.7, 1.6)]. When stratifying by median high school household income, no relationship was observed for the 2019–2020 academic school year. When stratifying by state, Alabama, and Pennsylvania demonstrated similar results, while Delaware, Illinois, Maryland, and Michigan observed no relationship for the 2019–2020 and 2020–2021 academic school years.

DISCUSSION

The main findings of this study were that while there was an overall 26% reduction in high school sport participation, different socioeconomic strata demonstrated different participation reductions, with lower socioeconomic strata demonstrating a smaller decrease in participation (<$30,000: 11%; $30,000 to $50,000: 5%; $50,001 to $100,000: 40%; >$100,000: 24%). Lower socioeconomic strata reported greater increases in pandemic injury incidence, ranging from 69% to 91%, compared to higher socioeconomic strata ranging from 41% increase to a 6% decrease in injury incidence. Athletes of lower socioeconomic status that participated in collision sports demonstrated an increase in injury incidence ranging from 159% to 213%, with the highest socioeconomic strata demonstrating only a 10% increase in injury incidence during the pandemic academic school year. A unit increase in median high school household income was associated with a
Table 1. Injury Incidence Proportion Stratified by Socioeconomic Status and by Gender and Severity

<table>
<thead>
<tr>
<th>Injury IP</th>
<th>Identified Gender IP</th>
<th>Minor</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>19-20: n: 98,487</td>
<td>15.7 (15.5, 15.9)</td>
<td>19.4 (19.1, 19.7)</td>
<td>17.0 (16.7, 17.3)</td>
<td>23.4 (23.0, 23.8)</td>
</tr>
<tr>
<td>20-21: n: 72,521</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;$30,000</td>
<td>19-20: n: 806</td>
<td>15.6 (13.1, 18.1)</td>
<td>26.3 (23.1, 29.6)</td>
<td>17.8 (14.3, 21.4)</td>
</tr>
<tr>
<td>20-21: n: 717</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$30,000 to $50,000</td>
<td>19-20: n: 5,114</td>
<td>7.8 (7.1, 8.6)</td>
<td>14.9 (13.8, 15.9)</td>
<td>7.2 (6.5, 8.0)</td>
</tr>
<tr>
<td>20-21: n: 4,882</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$50,001 to $100,000</td>
<td>19-20: n: 49,079</td>
<td>15.1 (14.7, 15.4)</td>
<td>21.3 (20.9, 21.8)</td>
<td>16.0 (15.5, 16.4)</td>
</tr>
<tr>
<td>20-21: n: 34,310</td>
<td></td>
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<td></td>
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<tr>
<td>&gt;$100,000</td>
<td>19-20: n: 40,882</td>
<td>18.4 (18.1, 18.8)</td>
<td>17.3 (16.8, 17.7)</td>
<td>20.0 (19.5, 20.5)</td>
</tr>
<tr>
<td>20-21: n: 31,226</td>
<td></td>
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</tr>
</tbody>
</table>

IP = Incidence Proportion
Incidence proportion is per 100 athletes
All incidence proportion is reported with 95% confidence intervals
19-20 = Pre-pandemic academic school year
20-21 = Pandemic academic school year
<table>
<thead>
<tr>
<th></th>
<th>Collison</th>
<th>Field &amp; Court</th>
<th>Individual</th>
<th>Other</th>
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<tbody>
<tr>
<td></td>
<td>19-20</td>
<td>20-21</td>
<td>19-20</td>
<td>20-21</td>
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<tr>
<td>Overall</td>
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<tr>
<td>19-20: n: 98,487</td>
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<tr>
<td>20-21: n: 72,521</td>
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<tr>
<td></td>
<td>5.4</td>
<td>8.7</td>
<td>8.1</td>
<td>2.5</td>
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<tr>
<td></td>
<td>(5.2, 5.5)</td>
<td>(8.5, 8.9)</td>
<td>(7.9, 8.3)</td>
<td>(2.4, 2.6)</td>
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<td>(0.4, 0.6)</td>
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<td>&lt;$30,000</td>
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<td>19-20: n: 806</td>
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<td>20-21: n: 717</td>
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<td></td>
<td>5.7</td>
<td>15.6</td>
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<td>3.0</td>
<td>6.4</td>
<td>2.9</td>
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IP = Incidence Proportion
Incidence proportion is per 100 athletes
All incidence proportion is reported with 95% confidence intervals
19-20 = Pre-pandemic academic school year
20-21 = Pandemic academic school year

International Journal of Sports Physical Therapy
Table 3. Injury Incidence Proportion by Stratified by State and Socioeconomic Status

<table>
<thead>
<tr>
<th></th>
<th>Alabama</th>
<th>Delaware</th>
<th>Illinois</th>
<th>Maryland</th>
<th>Michigan</th>
<th>Pennsylvania</th>
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<td>Overall</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>19-20</td>
<td>7.4 (7.0, 7.8)</td>
<td>30.6 (29.9, 31.2)</td>
<td>22.4 (21.7, 23.2)</td>
<td>16.2 (15.4, 17.2)</td>
<td>11.0 (10.7, 11.4)</td>
<td>21.2 (20.5, 21.9)</td>
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<td>22.1 (18.7, 25.5)</td>
<td>28.4 (23.3, 33.5)</td>
<td>44.7 (35.5, 51.8)</td>
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<tr>
<td>19-20</td>
<td>29.7 (26.7, 32.7)</td>
<td>21.2 (18.8, 23.4)</td>
<td>16.2 (13.8, 18.6)</td>
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<td>12.3 (11.0, 13.6)</td>
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<tr>
<td>19-20</td>
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<td>30.2 (29.4, 30.9)</td>
<td>22.9 (22.0, 23.7)</td>
<td>17.0 (16.1, 18.0)</td>
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</tbody>
</table>

IP = Incidence Proportion
Incidence proportion is per 100 athletes
All incidence proportion is reported with 95% confidence intervals
19-20 = Pre-pandemic academic school year
20-21 = Pandemic academic school year
Table 4. Injury Incidence Proportion by Stratified by State and Socioeconomic Status.

<table>
<thead>
<tr>
<th>Stratified household income</th>
<th>Actual Injury Count 19-20</th>
<th>Predicted Injury Count 19-20 (95% CI)</th>
<th>Actual Injury Count 20-21</th>
<th>Predicted Injury Count 20-21 (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>15,477</td>
<td>15,376 (11,096, 22,099)</td>
<td>14,057</td>
<td>12,096 (9,640, 17,533)</td>
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<tr>
<td>Severe Injuries</td>
<td>6,665</td>
<td>6,597 (4,877, 9,078)</td>
<td>4,690</td>
<td>4,426 (3,092, 6,341)</td>
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<tr>
<td>Moderate Injuries</td>
<td>4,784</td>
<td>4,744 (3,402, 6,560)</td>
<td>5,655</td>
<td>5,056 (3,510, 7,286)</td>
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<tr>
<td>Stratified household income</td>
<td>15,477</td>
<td>15,375 (10,720, 22,381)</td>
<td>14,057</td>
<td>13,255 (9,401, 18,975)</td>
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<td>Alabama</td>
<td>1,191</td>
<td>1,186 (698, 2,039)</td>
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<td>5,478 (4,492, 6,796)</td>
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<td>Delaware</td>
<td>2,347</td>
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<td>3,783</td>
<td>3,775 (1,931, 8,762)</td>
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<td>2,497 (1,613, 4,109)</td>
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<td>Maryland</td>
<td>4,302</td>
<td>4,149 (2,663, 6,408)</td>
<td>806</td>
<td>788 (478, 1,288)</td>
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<td>Michigan</td>
<td>2,178</td>
<td>2,173 (1,654, 2,973)</td>
<td>2,126</td>
<td>2,125 (1,610, 2,902)</td>
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<td>Pennsylvania</td>
<td>1,191</td>
<td>1,186 (698, 2,039)</td>
<td>1,607</td>
<td>1,622 (1,073, 2,472)</td>
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</tbody>
</table>

95% CI = 95% Confidence Interval
19-20 = Pre-pandemic academic school year
20-21 = Pandemic academic school year

60% increase in injury incidence in the 2019-2020 academic school year; but no association was observed for the pandemic academic school year.

Lower socioeconomic strata demonstrated increased injury incidence during the 2020-2021 academic school year, with the highest socioeconomic strata of $100,000+ median household income demonstrating similar injury incidence between school years. Further, lower socioeconomic males demonstrated the greatest increase in injury incidence. These differences in injury incidence may be related to recreational and sport facility access. Lower socioeconomic people have less access and quality of recreational and sport facilities. People from lower socioeconomic strata generally have increased fear of violence and increased barriers to performing physical activity and exercise. Concerning high school athletes, athletes from lower socioeconomic strata have demonstrated reduced training time per week. During the prolonged cessation of high school sport, athletes from lower socioeconomic strata may have had reduced access and time to train and practice sport compared to higher socioeconomic athletes, providing increased deconditioning and loss of sport specific skill, subsequently increasing injury incidence.

Lower socioeconomic collision sport participants demonstrated a two to three times increase in injury incidence during the 2020-2021 academic school year, while the highest socioeconomic strata demonstrated similar collision injury incidence between the 2019-2020 and 2020-2021 academic school years. High school collision sports such as football, lacrosse, and wrestling have previously demonstrated the greatest injury incidence, compared to field and court and individual sports. Collision sports also require further physical preparation beyond general fitness and strength, due to athlete to athlete collisions. The repetitive physical trauma involved in collision sport requires physical adaptations to handle the high impact forces involved in tackles and blocking. This supports previous research where decreased off season and preseason training demonstrated greater injury incidence in collision sports, suggesting a truncated preseason predisposes an athlete to greater musculoskeletal injury risk in this population compared to other sports.

A proportional association was observed between injury incidence and median high school household income in the 2019-2020 academic school year after controlling for confounders. These results support previous research concerning socioeconomic status and injury incidence. One study observed that low material wealth was a protective effect against sport injuries. However, this study examined adolescent injuries in 35 countries, and specific comparisons of sport participation was not performed. As many countries do not provide school sponsored sports, socioeconomic status can be a barrier to sport participation in many countries. However, in this study, sport participation...
in relation to overall high school population was controlled for, and these athletes solely participated in sport within the United States, decreasing the transferability of this literature to this study's findings. A possible explanation is that lower socioeconomic high school athletes are more prone to decreased injury reporting compared to higher socioeconomic high school athletes.\textsuperscript{37,58} Lower socioeconomic athletes may have greater fear of losing playing time, differences in self-regulation, or health care access outside of school athletics.\textsuperscript{37} However, injury under reporting may be for only minor or moderate injuries. Within the sensitivity analyses, severe injury incidence ratios were similar between socioeconomic strata. The similar severe injury incidence between strata may be due to the nature of severe injuries, which can cause greater limits on sports performance and function compared to moderate or minor injuries.\textsuperscript{40} These greater physical and sport specific limitations may be associated with a greater propensity of lower socioeconomic status high school athletes to report these injuries. However, further research is needed to investigate these potential discrepancies.

No association between median household income and injury incidence was observed for the 2020-2021 academic school year. As stated previously, higher socioeconomic strata demonstrated similar injury incidence between the academic school years; however, lower socioeconomic strata reported an increased in injury incidence. The conflicting findings between socioeconomic status and injury incidence ratios between the pre-pandemic and pandemic academic school years may be related to secondary effects related to COVID-19 vulnerability.\textsuperscript{58,59} The increased injury incidence in lower socioeconomic strata may have negated the injury underreporting effect during the pandemic academic year. Further qualitative and quantitative research into barriers and facilitators of injury reporting and risk are needed within these populations to understand potential solutions to socioeconomic athlete injury discrepancies.

LIMITATIONS

Due to the nature of high school sport and resource availability, it was not possible to collect more granular exposure data such as practice or competition minutes. This precludes injury rate calculations, decreasing the clinical usefulness of these incidence and model results. COVID-19 infection rates changed throughout the reporting period, and were different for the included states, decreasing the precision of these results. The included states reported different prevalence of high school socioeconomic strata, biasing the results towards the null. Recruitment was based on athlete coverage by the sports medicine organization and sport participation during the 2020-2021 academic year, increasing risk of recruitment bias and non-response bias. There are inherent yearly fluctuations in injuries at the high school and state level. This study only had access to one year of injury data prior to the COVID-19 pandemic, decreasing the precision of these results. Due to the ecological nature of this study, individual injury history, strength, range of motion, balance, and sport experience were not available, resulting in unmeasured confounding that could bias these results. Causality cannot be inferred from these data, with future causal study design required to understand the cause and effect of abrupt prolonged sport stoppage.

CONCLUSION

Lower socioeconomic high schools reported increased injury incidence compared to higher socioeconomic high schools during the 2020-2021 academic school year. This relationship was most pronounced in males and within collision sports. The highest socioeconomic high school strata reported similar injury incidence between academic school years, suggesting greater access and time to exercise, training, and sport practice during the abrupt high school sport stoppage. Increased high school socioeconomic status was associated with a statistically significant increased injury incidence within the 2019-2020 but not the 2020-2021 academic school years. These results highlight the secondary downstream COVID-19 pandemic associations and the increased potential pandemic vulnerability in lower socioeconomic high school athletes. Sports medicine clinicians, high school administrators, and policy makers need to consider the magnified effect abrupt stoppage from high school sport practice and competition can incur in lower socioeconomic high school athlete injuries when designing return to sport protocols. Expanded preseason and inquiries into previous training and practice habits may be required for more vulnerable high school athletes when returning to sport.

ACKNOWLEDGEMENTS

The authors would like to thank Chris Le, PT, PhD for her helpful editorial comments.

FUNDING

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CONFLICTS OF INTEREST

None

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REFERENCES


SUPPLEMENTARY MATERIALS

Appendix
Original Research

Understanding Youth Athlete Motivation, Training, and Activity Progression During and After the COVID-19 Sports Interruption

Elliot Greenberg¹,², Eric Greenberg¹, Todd Lawrence¹,³, Theodore Ganley¹,⁴

¹ Sports Medicine and Performance Center, Children's Hospital of Philadelphia, ² Department of Physical Therapy, New York Institute of Technology, ³ Division of Orthopaedic Surgery, Children's Hospital of Philadelphia, ⁴ Department of Orthopaedic Surgery, University of Pennsylvania

Keywords: Covid-19, exercise, training, pandemic, youth athlete

https://doi.org/10.26603/001c.40372

International Journal of Sports Physical Therapy

Background

COVID-19 restrictions created a period of disrupted sports participation for youth athletes. The physical conditioning, sports training habits, and patterns of sports activity resumption upon returning to normal sports activity are currently unknown.

Purpose/Hypothesis

This study aimed to determine the extent to which youth athletes maintained their training levels during the early stages of the COVID-19 pandemic and understand the strategies that enhanced motivation and adherence to a training regimen while in isolation. A secondary aim was to analyze how youth athletes returned to activity and identify injuries associated with prolonged sports interruption.

Study Design

Observational / Survey Study

Methods

A survey designed to determine activity changes, type of organized instruction, and athlete preferences for training support were distributed by email using snowball sampling methodology to athletes 14-21 years old who were involved in competitive sports when pandemic restrictions were enacted. As sports activities resumed, a follow-up survey was distributed to the same respondents to identify feelings of preparedness, training habits, and injuries.

Results

Of the 155 subjects (mean age 16.1 ± 2 years, 64.5% female) that completed the initial survey, 98% reported a stoppage of in-person sports participation and 70% decreased their exercise/training volume, with 41% (n=63) reporting > 50% reduction. Most athletes (86%) received instruction from coaches, with written workouts (70%) being most common; however, most athletes (70%) preferred instructor-led, group training sessions. Of the 43 subjects that completed the follow-up survey (54% response rate), there was an increase in athletic exposures compared to mid-pandemic levels, and 25% reported sustaining a sports-related injury shortly after resuming sports activities.

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Chalfont, PA 18914
Email: greenberge@chop.edu
Conclusions

Pandemic-related sports restrictions resulted in a significant reduction in youth athlete training and conditioning. Coaches attempted to maintain training via the use of written workouts; however, athletes preferred instructor-led, group training sessions. There was a rapid resumption of sports activities, which may have contributed to the high rate of injuries in this study.

Level of Evidence

3

INTRODUCTION

The SARS-CoV-2 coronavirus and COVID-19 pandemic reached epic proportions at the start of the Spring and Summer sports seasons in 2020. In attempts to limit the spread of disease, intermediate schools, high schools, and colleges across the United States transitioned to remote learning strategies and suspended any formal interscholastic sports activities and extracurricular events.

The Center for Disease Control recommends that children participate in at least 60 minutes of vigorous activity daily. The maintenance of fitness and skill development is crucial for sports performance and injury risk reduction. However, in the Fall of 2020, six months following the sports shutdown, only 14 US states allowed full Fall sports participation, while the remaining states permitted either modified or no athletics due to the COVID-19 restrictions.

Prolonged decreases in physical activity levels can result in adverse physiological consequences across multiple body systems, including the cardiovascular, respiratory, musculoskeletal, and endocrine systems. Recent evidence further highlights the adverse psychological consequences associated with the COVID-19 restrictions in both adult and youth athlete populations. Thus, enriching athlete motivation and adherence to prescribed training programs are of utmost importance to maintain physical activity, enhance emotional and mental health, and decrease injury risk. Currently, there is limited understanding of how youth athletes train while away from the traditional team environment during the COVID-19 sports interruption.

Additionally, the specific factors that increased motivation to maintain physical fitness and athletic performance during this time are currently unknown. This study aimed to determine the extent to which athletes maintained their training levels during the COVID-19 pandemic and understand the strategies that enhanced motivation and adherence to a training regimen while in physical isolation. A secondary aim was to further understand how youth athletes returned to activity and identify any secondary effects of the prolonged sports interruption as they resumed athletic activities.

METHODS

A team of two physical therapists and two orthopedic surgeons specializing in the treatment of youth athletes developed a two-part electronic survey in REDCap, hosted by The Children’s Hospital of Philadelphia. The initial survey aimed to determine activity changes, the current level of organized instruction, and athlete preferences for ongoing training support during the pandemic-related stoppage of in-person sports activity in the spring/summer of 2020. The initial survey contained six components: eligibility screening, general and sports demographics, current and previous training volumes, type of instruction received, individual training preferences, and perceptions of a future return to activity (Appendix A). After sports activities had resumed, a follow-up survey was distributed to the same cohort to understand athlete perceptions and experiences of sports resumption after the prolonged period of forced reduction in team-based activities (Appendix B).

The development of each survey instrument followed a similar process. Initial development identified key topics and consensus regarding survey structure and question format. The survey was pilot-tested and refined after consultation with a small group of youth athletes representing the population of interest. The final surveys consisted of multiple-choice questions and took approximately four to six minutes to complete.

To be eligible for this study, subjects needed to be between 14 and 21 years old and actively engaged in competitive sports at the onset of the pandemic-restricted in-person sports activities. The initial survey was distributed directly to athletes by email, using a snowball sampling methodology starting with the primary team of authors’ personal, professional, and community connections. The survey period began in June 2020 and remained open for eight weeks. The secondary survey was distributed in October 2020 to those individuals who consented to follow-up questioning while completing the initial survey. The subjects received a single email invitation and one reminder email to complete the follow-up survey. This survey remained open for a period of four weeks. This study was reviewed and approved by the Institutional Review Board at The Children’s Hospital of Philadelphia.

RESULTS

INITIAL SURVEY

The survey was accessed a total of 266 times. Ninety-eight individuals accessed the survey consent and/or eligibility screening portions but did not complete the survey. Thus, a total of 168 subjects met eligibility and were included in Phase 1 of this study. The mean age of the sample was 16.3 ± 2.1 years. Subjects were 62% female, predominantly white (95%), and mainly from Pennsylvania (54%), New Jersey...
Table 1. Subject Demographics

<table>
<thead>
<tr>
<th>Subject Demographics</th>
<th>Initial Survey (n=168)</th>
<th>Follow-up Survey (n=43)</th>
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<td>Age, years (mean ± SD)</td>
<td>16.3 ± 2.1</td>
<td>16.3 ± 2.0</td>
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<tr>
<td>Sex, n (%)</td>
<td>Female, 104 (62%)</td>
<td>Female, 28 (65%)</td>
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<tr>
<td>Race, n (%)</td>
<td>White, 160 (95%)</td>
<td>White, 42 (98%)</td>
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<td>Type of School Attended, n (%)</td>
<td>Public, 114 (68%)</td>
<td>Public, 28 (65%)</td>
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<td></td>
<td>Private, 24 (14%)</td>
<td>Private, 6 (14%)</td>
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<td>College or University, 32 (19%)</td>
<td>College or University, 9 (21%)</td>
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<td>Type of Sport played, n (%)</td>
<td>Soccer, 63 (38%)</td>
<td>Soccer, 18 (42%)</td>
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<td>Lacrosse, 34 (20%)</td>
<td>Swimming, 6 (14%)</td>
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<td>Track &amp; Field, 28 (17%)</td>
<td>Lacrosse, 4 (9%)</td>
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<td>Team Type, n (%)</td>
<td>School Based, 54 (32%)</td>
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<td>Club or Private, 46 (27%)</td>
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<td>Both, 68 (40%)</td>
<td>Both, 24 (56%)</td>
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</tbody>
</table>

(19%), and New York (10%). While subjects reported participating in a total of 22 different sports, the majority of subjects participated in soccer (38%), lacrosse (20%), and track and field (17%) (Table 1).

Nearly all (98%) of subjects reported that in-person practices and sports-related activities were canceled due to the COVID-19 pandemic. Most athletes (86%) reported receiving sports-related training instructions from their coaching or training staff during this time. Written workouts represented the most common method of instruction (70%). However, "live" online sessions via Zoom or similar platforms represented 53% of instructions, and pre-recorded videos accessed through YouTube or other platforms were also commonly utilized modes (33%) (Figure 1). A large proportion of athletes (73%) reported supplementing team-based training recommendations with individually designed workouts, most frequently jogging (62%), strength training (54%), and sports-specific drills (51%). Despite team-based training suggestions and individual supplemental workouts, only 21% of the sample reported their weekly training hours remained similar to their pre-pandemic levels. Most subjects (67%) reported a decrease in their overall weekly training volumes, with 40% of athletes reporting their training volumes decreased by more than half of their pre-pandemic levels. Along with reduced training volumes, many youth athletes (40%) indicated they would not feel physically prepared to resume in-person sports-related activities.

Improving athletic skill and performance was the primary motivator (66%) to independently train while not participating in in-person activities, followed by being healthy (50%), and improving their physical appearance (30%). Interestingly, a small number of athletes indicated they trained due to coaches' (18%) or parents' (6%) expectations.

When asked about their preferred remote training methods, a large majority of athletes felt their performance was best when training in an online "live" group setting led by a coach or trainer (70%). Only a small subset of athletes felt at their best while training with a written-guided workout (25%) or independently designing their workouts (5%) (Figure 2).

FOLLOW-UP SURVEY

One hundred forty-four subjects indicated consent to participate in Phase II of this study. A total of 49 subjects (response rate 34%) accessed the follow-up survey. Six athletes had not resumed in-person sports activities yet, leaving 43 subjects who completed the follow-up survey.

The demographics and subject characteristics were similar between the initial and secondary survey participants (Table 1). A majority of athletes felt either moderately (60%) or extremely prepared (21%) for in-person sports activities. Approximately 50% of athletes reported initially resuming in-person activities with more than one sports team. When practices initially resumed, athletes indicated a nearly even split of practice frequency between 1-2 days per week (35%), 3-4 days per week (30%), and 5-7 days per week (35%), however at the time of survey completion, the frequency of practices increased to 5-7 days per week for 63% of the sample (Figure 3). Despite this increase in practice frequency, 65% of the sample reported they still supplemented team-based practices with jogging (51%), sports-specific skill work (47%), and strength training (40%) on an individual basis. A return to competitive game activities was reported to occur within the first month of resuming in-person practices for 34% of the sample.

Since the resumption of in-person sports activity, 28% of the sample reported experiencing "aches or pains that limited their ability to participate in sports." Notably, nearly 25% of the sample reported they sustained an injury requiring them to visit a doctor, urgent care, or another medical provider, with muscle strains (70%) and torn ligaments (20%) making up most of the diagnoses.

DISCUSSION

Infection mitigation precautions adopted in response to the COVID-19 pandemic created a rapid change in the sports environment for youth athletes. The results of this study are the first to present specific information related to activity changes, athlete perception of training effectiveness, and self-reported injuries during the period of organized
Figure 1. Mode of sports-related instruction provided to athletes during the COVID-19 sports shutdown

Figure 2. Athlete training preferences during the COVID-19 sports shutdown

There was a substantial reduction in youth athlete training and sports conditioning amidst COVID-19-related sports restrictions, with nearly 40% of the sample reporting participating in less than half of pre-pandemic weekly hours of sports activity. These data expand upon previously published reports demonstrating decreased physical activity due to social distancing prevention protocols in response to the COVID-19 pandemic across various populations. The reduction in training volumes experienced during the pandemic poses an interesting situation. Excessive sports volumes, competition congestion, and limited rest intervals have all been suggestive of creating an increased risk of musculoskeletal injury in youth athletes.\(^8,9\) Therefore, the reduction in training volume brought about by the pandemic may have served as a much-needed break from sports-specific training for these young athletes. This
suggestion is further supported by data from a multi-center study finding a decrease in sports-related musculoskeletal injuries amongst youth athletes during the COVID-19 pandemic.\textsuperscript{10} Though this change in activity may have been protective in the short term, these behaviors may become problematic as COVID-related sports restrictions decline. While this survey cannot quantify specific relationships between acute and chronic workloads, the subjects indicated a significant decrease in overall training hours during socially distant sports protocols, followed by a rapid resumption of in-person athletic activity (Figure 3). In addition, approximately 30% of subjects reported immediately returning to play for more than one sports team, which may contribute to overall increased sports-related workloads. Several studies have demonstrated an increased risk of injury with acute spikes or rapid alterations in an athlete's acute workload compared to their chronic workloads and current fitness levels.\textsuperscript{11–13} This concept may help explain why 25% of the sample required medical attention for an injury within a mean time of 79 days after resuming in-person sports activity. While a small number of follow-up respondents limits the strength of these conclusions, these findings are consistent with previous studies that found an increased rate of injuries and earlier time to injury within older groups of athletes upon returning to competitive sports after COVID-related sports interruptions.\textsuperscript{14–16} Though it is unknown whether maintenance of physical activity workloads during time away from organized sports could have mitigated this injury risk, future studies should seek to evaluate these factors more specifically. This information could help inform more effective youth fitness programs during ongoing and future pandemic mitigation strategies. These findings may also inform coaches, parents, athletes, and healthcare practitioners about injury prevention efforts after a prolonged absence from team-based sports activity, such as after recovering from significant injury, surgery, or other circumstances necessitating a particularly inactive period between sports seasons.

In addition to the potential role in mitigating injury risk, the direct relationship between physical activity and mental health is well established.\textsuperscript{17–19} Recent studies have highlighted the adverse consequences on mental health and quality of life for youth athletes during this pandemic.\textsuperscript{6,20,21} Collectively, the data from the current study and these previous reports highlight the relationship between exercise and training in maintaining an athlete's physical and psychological well-being.

To maximize youth athlete compliance with recommended training activities, athlete preferences of instruction mode should be considered. While coaches and training staff attempted to maintain physical activity using various methods, the primary means was via written handouts. While this instruction method offers several benefits regarding ease of administration and adaptability, it did not match athlete preferences for virtual "live" or recorded instruction. Exercise instruction that matches athlete or patient preferences may improve maintenance of physical activity through enhanced motivation and exercise participation. Issues of compliance with recommended physical activity levels or home-exercise prescriptions are problematic amongst healthy and injured populations.\textsuperscript{22} Inadequate exercise amongst children may contribute to suboptimal athletic performance and future health consequences.\textsuperscript{7,23} Thus, the utilization of effective and motivational exercise communication strategies should be of high priority. Previous studies have shown improved com-

Figure 3. Training Volume (days/week) of participants during the COVID-19 sports shutdown and following the resumption of in-person activities
pliance to prescribed exercises using video-based exercise instruction.24,25 Youth athletes in the current world are technologically savvy and highly digitally connected through smartphones and other devices and, not surprisingly, indicated a preference for synchronous and asynchronous web-based exercise instruction. In addition, youth athletes indicated they were most motivated to exercise or train to improve their athletic performance and health. Though future studies examining instruction mode on compliance are needed, coaches, healthcare practitioners, and other sports-related professionals should consider employing the more preferred video-based exercise instruction.

Approximately 75% of youth athletes indicated they supplemented coach-supplied training instructions with independent workouts during the forced hiatus of in-person activities. While this was not unexpected, the authors found it surprising that 65% of athletes continued to supplement in-person sports with their routines once in-person activities had resumed. Coaches and medical staff typically base exercise or training volume progression decisions on the assumption that they understand their athletes’ current training volumes. The data from this survey suggests that a large proportion of youth athletes are pursuing further training than what is provided during monitored training sessions. Medical staff and coaches should consider questioning their athletes about independent training habits or use automated technology-based workload monitoring methods to understand their athletes’ training habits more accurately. This information would help guide prescriptive workload decisions and may help reduce the potential for overuse injuries among youth athletes.

LIMITATIONS

There are several limitations to this study that should be recognized. The survey questionnaires were not previously validated, and although efforts were made to ensure clarity and accurate interpretation during development and pilot testing, individual variations in the interpretation of questions may exist. Nearly all of the sample came from the Northeastern United States and were predominately white; thus, the results of this study may not be generalizable to a broader population. The sample size for the follow-up survey was smaller than the original survey and may create bias thus, the results of the follow-up survey should be taken with caution. Finally, the snowball, electronic sampling methodology could have led to a sampling bias by sharing this survey within groups of athletes with similar social, demographic, or physical characteristics, which may limit the generalizability of these results.

CONCLUSION

In-person sports activity restrictions brought about by the mitigation efforts to reduce the spread of Covid-19 created an acute decrease in youth athlete training and exercise volumes. Athletes preferred using online video platforms to engage in remote training instruction. Though most athletes supplemented training activities with individualized training, many significantly declined physical activity during the time of pandemic-related sports restrictions. These reported changes in training habits and volumes may have contributed to a high injury rate among study participants following the resumption of organized sports activities. By understanding youth athlete training preferences, the results of this study can help professionals working with youth athletes maximize compliance with home-based exercise instruction, enhance youth physical fitness, and mitigate the adverse physical and psychological health sequelae of inactivity.

CONFLICT OF INTEREST STATEMENT

We, the authors, affirm that we have no financial or commercial affiliations related to the performance or outcome of this manuscript.

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IRB STATEMENT

Institutional Review Board of The Children’s Hospital of Philadelphia approved this study. Protocol #: 20-017595

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REFERENCES


Effects of Trigger Point Dry Needling on Strength Measurements and Activation Levels of the Gluteus Medius: A Quasi-Experimental Randomized Control Study

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Keywords: gluteus medius, latent trigger points, muscle activation levels, muscle strength, trigger point dry needling, myofascial trigger points

Original Research

International Journal of Sports Physical Therapy

**Background**
Latent trigger points have been identified as a source of impaired muscle function giving rise to a reduction in force production and alterations in muscle activation patterns and movement efficiency. There is limited investigation into the effectiveness of a treatment in reducing these clinical manifestations.

**Purpose**
To investigate whether the application of trigger point dry needling (TDN) to latent trigger points within the gluteus medius musculature affected strength measurements and muscle activation levels immediately following intervention.

**Design**
Quasi experimental, single group, pretest-posttest, randomized control study

**Methods**
A control and an intervention side were randomly assigned for each participant \(N = 39\). Hand held dynamometer (HHD) force measurements and raw surface electromyography (sEMG) amplitude readings were recorded during maximal volitional isometric contractions of the gluteus medius in two separate positions before and after application of TDN. Comparison of within and between group data were conducted.

**Results**
A statistically significant interaction between time (pre-TDN to post-TDN) and groups (intervention side and control side), \(p < 0.001\) was found for HHD measurements in both positions. Post hoc analysis revealed a statistically significant difference \((p < 0.001)\) for all comparisons in the side lying neutral (SL0) position, while statistically significant differences \((p < 0.001)\) were found for pre and post-TDN measurements within intervention side as well as between the intervention and control side for post-TDN measurements in the side lying internal rotation (SLIR) position. For sEMG amplitude measurements, statistically significant differences were found only in the SL0 position for within group comparisons on the intervention side \((p = 0.009)\) and for between group comparisons for post-TDN measurements \((p = 0.002)\).
Conclusion

Application of TDN to latent trigger points within the gluteus medius can significantly increase gluteus muscle force production immediately following intervention while reducing the level of muscle activation required during contraction.

Level of Evidence

Level 2

INTRODUCTION

Myofascial trigger points (MTrPs) have been identified as a potential source of musculoskeletal dysfunction.1–5 Myofascial trigger points have been defined as hyperirritable and palpable nodules within a taut band of muscle and are classified as either active trigger points or latent trigger points.6 Active trigger points can cause localized pain that is spontaneous in nature,4,5 while latent trigger points are not spontaneously painful and will only elicit pain when palpated.3–5 Some authors have argued that latent trigger points have the same pathophysiology as active trigger points, just to a lesser extent,3–5,7 which may explain a reduction in nociceptive input without mechanical stimulus.8–10

Most of the research on MTrPs has focused on active trigger points due to their ability to generate spontaneous pain without being palpated, even though latent trigger points are more commonly found in muscle tissue.11,12 Despite a lack of attention in the literature, latent trigger points are not without clinical significance. Regarding function, they have been found to increase muscle fatigability,13 decrease muscle strength,14 and alter muscle activation patterns.1,15 Furthermore, latent trigger points may have the potential to transition into active trigger points if left untreated.7

Trigger point dry needling (TDN) has become an increasingly popular intervention among physical therapists to reverse the effects of MTrPs.16,17 Authors of previous studies have demonstrated a reduction in substance P and calcitonin related peptide levels, while blood flow and subsequent tissue oxygenation increased following the application of TDN to MTrPs.8,18 However, there is still debate surrounding the effectiveness of TDN provided by physical therapists as a viable treatment option for musculoskeletal dysfunction as compared to other physical therapy interventions.19

A potential cause for the formation of MTrPs has hypothesized to be repetitive or unaccustomed eccentric loading of muscle tissue.4,5,7,20–22 Musculature such as the gluteus medius must eccentrically control motion of the pelvis within the frontal plane during the gait cycle23 or during other functional activities where single limb support is required.24 Subtle alterations in frontal plane gait kinematics may lead to excessive loading of the gluteus medius musculature, which in turn may lead to the formation of MTrPs. If latent trigger points are able to affect muscle function, then an asymptomatic individual may have altered stability of the pelvis and the hip during loading response of the gait and running cycles, which then has the potential to alter the alignment of the lower limb relative to the ground.

Despite the increased demand for eccentric control during functional activities, such as ambulation, there are no studies that have investigated the effects of latent trigger points on the strength of the gluteus medius. Furthermore, studies that have investigated changes in strength of lower extremity musculature following the application of dry needling to MTrPs report conflicting results.25–32 The purpose of this study was to investigate whether the application of TDN to latent trigger points within the gluteus medius musculature affected strength measurements and muscle activation levels immediately following intervention.

METHODS

STUDY DESIGN

This quasi-experimental study used a single group, pretest-posttest, randomized control design (www.ClinicalTrials.gov, ID NCT03580200). The study was approved by the Human Research Protections Program at the University of Indianapolis and a reliance agreement was enacted with Mount St Joseph University in Cincinnati, OH where data were collected.

PARTICIPANTS

A convenience sample of males and females age 18 to 50 years old were recruited provided they were asymptomatic at the time of screening and data collection. Asymptomatic was defined as experiencing no pain in the lumbar spine, sacroiliac region, pelvis, or bilateral lower extremities while at rest or with activity. Participants were excluded if they had one of the following: were pregnant or attempting to become pregnant; pain intensity greater than 0 out of 10 on the visual analogue scale in the lumbar spine, sacroiliac region, pelvis, and bilateral lower extremities at rest or with activity; positive Flexion Adduction Internal Rotation test (FADIR)33 on either the left or right hip; presented with signs and symptoms consistent with hip osteoarthritis during clinical screening using the criteria proposed by Altman et al.34; diagnosed with a progressive neurological disorder, a chronic pain condition such as fibromyalgia or myofascial pain syndrome, a connective tissue disorder, or osteoarthriti of the hip joint; history of hip dysplasia or Legg Calve Perthes disease.

Informed consent was obtained following eligibility screening but immediately prior to data collection. The primary investigator (PI), a licensed physical therapist with 13 years of clinical experience was responsible for data collection and the application of TDN for all participants throughout the study.
RANDOMIZATION

A simple randomizing method of flipping a coin was used to assign each participant an intervention side, which was the side of the body that received TDN, and a control side, which was the side of the body that did not receive TDN.

OUTCOME MEASURES

Strength of the gluteus medius muscle was defined as the amount of force output measured by a handheld dynamometer (HHD) during a maximal volitional isometric contraction (MVIC) break test.\textsuperscript{35–37} Force output was measured in kilograms (kg) using a microFET2 HHD (Hoggan Scientific, LLC, Salt Lake City, UT) on both the control and intervention sides. The HHD is commonly used to assess force production and has been shown to be a reliable and valid measurement tool for assessing strength of the lower extremity musculature.\textsuperscript{36,38–40}

Surface electromyography (sEMG) amplitude readings of the gluteus medius were recorded at the same time as HHD measurements on both the control and intervention sides. Raw sEMG data were collected using a two-channel sEMG recording system (MP36R, Biopac, Goleta, CA) and were measured in millivolts (mV). Parameters for recording the raw sEMG data included a rejection ratio of > 110 dB at 60 Hz, a gain of 1000 Hz, band pass filtered at 20–450 Hz, and a sampling rate of 2000 Hz.\textsuperscript{37,41,42} Recorded sEMG amplitude readings can be used as a direct measure of the activation level of a muscle during a contraction\textsuperscript{43–45} and is a common method of assessing the activation level of the gluteus medius muscle during a MVIC as well as dynamic movements.\textsuperscript{37,41,42,46–48}

Prior to the start of data collection, intrarater and test-retest reliability was established for the PI’s HHD and sEMG measurements during MVIC break testing of the gluteus medius. Ten participants with characteristics consistent with the study’s sample were recruited. A 10-minute break was given between measurements. All calculated ICCs (3, 1) were greater than .75 indicating acceptable intrarater and test-retest reliability\textsuperscript{49} (Table 1).

TESTING PROCEDURE

Bipolar sEMG electrodes were placed 2 cm apart in a position distal to the iliac crest, midway between the anterior and posterior superior iliac spines and in line with the proximal tip of the greater trochanter.\textsuperscript{41,42} A reference electrode was placed on the greater trochanter (Figure 1). Electrode placement on the intervention side was marked by a sterile surgical pen as electrodes needed to be removed during the application of TDN.

To ensure that the participant understood the position of testing, the leg to be tested was passively moved in to the testing position with verbal cueing. The pelvis was kept from rotating backwards by a manual stabilization force placed on the posterior and lateral iliac crest.\textsuperscript{35,36} The participant was then asked to assume the testing position without assistance, but with standardized verbal cueing from the PI. After the participant successfully achieved the proper position for testing without compensation on three consecutive attempts, a trial MVIC break test was performed.

Application of TDN to the gluteus medius was not limited to one specific region of the muscle. As such, all subdivisions of the gluteus medius muscle needed to be active during each MVIC break test. Using the recommendations of Otten et al.\textsuperscript{37} the hip was placed in two separate testing positions that were found to have the highest sEMG activation levels for all three subdivisions of the gluteus medius. Participants were positioned in side lying with their bottom or stabilization leg in a position of approximately 30 degrees of hip flexion and 90 degrees of knee flexion. The first testing position had the hip on the side being tested in a neutral or zero starting position (SL0) at the hip with the knee fully extended. Neutral or zero starting position was defined as a position where the hip is in neutral position with respect to hip flexion and extension, abduction and adduction, as well as internal rotation and external rotation (Figure 2). The second testing position had the hip in a position of neutral hip flexion and extension as well as abduction and adduction, but the hip was maximally internally rotated (SLIR) with the knee fully extended (Figure 3).

The resistance applied during each MVIC break test was applied gradually until maximal resistance was provided for a total of five seconds, or until the participant could no longer hold the testing position.\textsuperscript{35} To standardize the resistance applied for each trial as well as each participant, the entire body weight of the PI was placed 4 cm proximal to the lateral malleolus.\textsuperscript{35,36} The exact position of where the pressure should be placed was measured and marked on both the control and intervention sides.

Three MVIC break tests were performed first on the control side and then the intervention side. One minute of rest was given in between each test for both the SL0 and SLIR positions in an attempt to reduce the effects of muscular fatigue.\textsuperscript{47} If compensatory movements were observed during the recording of a strength measurement, the measure obtained was not recorded, the form was corrected and another test was performed. Once three valid tests were performed on the control and intervention each side, the HHD values were averaged.\textsuperscript{14,36} Following application of TDN, the same procedure for measuring strength and muscle activation levels of the gluteus medius was repeated.

INTERVENTION

Following the pre-TDN measurement of gluteus medius strength and muscle activation levels, latent trigger points were identified in the gluteus medius musculature on both the control and intervention sides using the methods proposed by Simons et al.\textsuperscript{40} Each participant was positioned in side lying with the hip on the side that was assessed in a slightly adducted position so normal muscle fibers were still on slack while the taut bands of muscle were placed under tension, which made them more easily palpable.\textsuperscript{11,12,14,15}

Participants needed at least two latent trigger points in the gluteus medius muscle on the intervention side in order to receive TDN.\textsuperscript{14} Trigger point dry needling was ap-
Table 1. Reliability of primary investigators HHD and sEMG measurements

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<tr>
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<th>Reliability of HHD and sEMG measurements within trials</th>
<th>Test retest reliability of HHD and sEMG measurements prior to and following 10 min break</th>
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<td>Pre 10 min break ICC* (95% CI)</td>
<td>HHD measurements ICC* (95% CI) sEMG measurements ICC* (95% CI)</td>
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<td>SL0 on R 0.96 (0.89 - 0.99) SLIR on R 0.92 (0.79 - 0.98) SL0 on L 0.94 (0.84 - 0.98) SLIR on L 0.95 (0.87 - 0.99)</td>
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<td>sEMG measurements</td>
<td></td>
<td>SL0 on R 0.83 (0.60 - 0.95) SLIR on R 0.92 (0.78 - 0.98) SL0 on L 0.96 (0.88 - 0.99) SLIR on L 0.93 (0.81 - 0.98)</td>
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Abbreviations: HHD = hand held dynamometer; sEMG = surface electromyography; ICC = intraclass coefficient; CI = confidence interval; SL0 = side lying neutral position; SLIR = side lying internal rotation position; R = right; L = left
lying internal rotation position; R = right; L = left

* (3, 1) model was used for ICC calculation

Figure 1. Surface EMG electrode placement for gluteus medius

Abbreviations: EMG = electromyography

LRT was elicited, the needle was manipulated either further into the muscle tissue or at a different angle until no more LTRs were elicited, or if the participant verbally requested the intervention to stop. Once the needle was removed, manual pressure was held at the site of needle insertion for a total of 30 seconds to achieve hemostasis.25,29 The same process was repeated for all identified latent trigger points within the gluteus medius muscle. The application of TDN was stopped when no more LTR were elicited and there were no more palpable latent trigger points.

Following the application of TDN, each participant was asked to stand up and walk for two minutes in an attempt to assess each participants’ level of soreness with functional movement. Time was managed by the PI for standardization purposes. Following the two minutes, participants were asked to rate their level of soreness on a 0 to 10 scale with a response of 0 representing, “No soreness at all” and a response of 10 representing, “The worst soreness imaginable”.

DATA MANAGEMENT

Biopac Student Lab software (Biopac, Goleta, CA) was used to analyze the recorded sEMG data. Raw sEMG readings were visually inspected and the peak amplitude that occurred during each MVIC was identified. Readings were then transformed using a root mean square calculation. Data were smoothed over 1000 points representing a 500 ms window around the identified peak amplitude, 250 ms prior to the peak and 250 ms following the peak.43 If the
500 ms window included readings that were not part of the MVIC, the next closest peak within the MVIC was identified and used. The mean amplitude within the 500 ms window was recorded for each trial.

Once a mean sEMG amplitude was found for each trial, the three trials in the SL0 and SLIR positions were averaged and recorded for both the intervention and control sides. The recorded HHD force measurements for all three trials in each position were also averaged and recorded for both sides. This process was performed for all measurements recorded prior to and following the application of TDN. The averaged values for the sEMG and HHD measurements were used for statistical analysis.

In order to be compared between trials or between individuals, sEMG readings must be normalized.44,45 The method of normalization has been debated, but normalization using a MVIC is a widely used44 and reliable method47 of comparing sEMG readings of the gluteus medius. The resultant sEMG data for measurements recorded prior to the application of TDN were used as the 100% MVIC reference for both the intervention and control sides. Averaged sEMG measurements recorded following the application of TDN were expressed as a percentage of the 100% MVIC.

STATISTICAL ANALYSIS

An a priori sample size estimation was conducted based on using a repeated measures ANOVA, analyzing the between-within interaction effect of four measurements between two groups and the following parameters, two-tailed test, alpha of 0.05, power of 0.80, a moderate effect size of 0.20. A minimum sample size of 36 participants was needed. To account for a potential participant dropout rate of 10% as well as individuals not presenting with latent trigger points in the gluteus medius when palpated, 40 participants were recruited.

All data were analyzed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY). Normality of the data was determined using the Shapiro-Wilk test. All comparisons were two-tailed and an alpha level of less than 0.05 was considered statistically significant unless otherwise noted. Effect sizes were interpreted using the recommendations of Cohen.50 Descriptive statistics were used to describe the baseline characteristics of the sample.

A two-way repeated measures ANOVA was used to assess if there was a significant interaction between time (pre-TDN and post-TDN) and groups (intervention side and control side) for HHD force measurements for the SL0 and SLIR positions. Post hoc analysis using paired t tests with a Bonferroni correction (alpha level of $p < 0.013$) were used to identify which pairs had a significant difference. Effect size of the interaction between time and groups were calculated (partial eta squared).

To assess whether there was a significant difference in sEMG measurements within the intervention side and the control side over time as well as between sides prior to and following the application of TDN, pairwise tests were conducted for both the SL0 and SLIR positions. Since sEMG data were not normally distributed, Wilcoxon signed-ranks tests with Bonferroni correction (alpha level of $p < 0.013$) were conducted. Effect sizes for the results of the Wilcoxon signed-ranks test were calculated (Cohen’s $d$) using the recommendations of Field.51

RESULTS

DESCRIPTION OF SAMPLE

Forty participants were recruited and met the inclusion criteria for the study. One participant’s results were excluded due to the protocol for data collection not being followed (Figure 4). Therefore, the total sample size for the study was 39 participants. Descriptive statistics for the baseline characteristics of the sample can be found in Table 2.

HAND HELD DYNAMOMETER

Hand held dynamometer measurements of force for the intervention and control sides for both the SL0 and SLIR positions are presented in Table 3 and Figure 5. There was a statistically significant interaction between the time (pre-TDN to post-TDN) and groups (intervention side and control side) for both positions, SL0 position, $F(1,58) = 107.89, p < 0.001$ and SLIR position, $F(1,58) = 95.37, p < 0.001$. The overall effect sizes were large for the interactions in the SL0 position (partial eta squared = 0.74) and the SLIR position (partial eta squared = 0.71).

Pairwise post hoc analyses were statistically significant ($p < 0.001$) for all comparisons in the SL0 position: pre-TDN to post-TDN within and between the intervention side and the control side for both time periods. For the SLIR position, there was a statistically significant difference ($p <
0.001) for pre-TDN and post-TDN measurements within the intervention side and between the intervention and control side for the post-TDN measurements. There was no significant difference ($p = 0.146$) within the control side when comparing pre-TDN and post TDN measurements, or when comparing pre-TDN measurements between the intervention and control sides ($p = 0.074$).

Hand held dynamometer measurements for the control side in the SL0 position decreased by 1.31 kg following the application of TDN. Three separate paired $t$ tests were used to assess differences between the three trials of HHD measurements taken on the control side following the application of TDN. Significant differences were found for the measurements recorded between trial 1 and trial 2 (mean difference = -0.71, $t(38) = -2.42, p = 0.020$) and trial 1 and trial 3 (mean difference = -0.97, $t(38) = -3.60, p = 0.001$). No significant difference was found between measurements recorded for trial 2 and trial 3 (mean difference = -0.26, $t(38) = -1.08, p = 0.287$).

**Surface Electromyography**

Surface EMG measurements of amplitude for the intervention and control sides for both positions are presented in Table 4 and Figure 6. Within group analysis revealed a statistically significant difference between pre-TDN and post-TDN sEMG amplitude measurements on the intervention side in the SL0 position $Z(39) = -2.60, p = 0.009$ with a medium effect size (Cohen’s $d = 0.62$). There were no statistically significant differences between pre-TDN and post-TDN sEMG amplitude measurements in the SL0 position on the control side, $Z(39) = -1.46, p = 0.145$. For the SLIR position, there was no statistically significant difference within either the intervention side, $Z(39) = -2.09, p = 0.037$ or the control side, $Z(39) = -1.00, p = 0.317$.

Between TDN group comparisons for the SL0 position revealed there was not a statistically significant difference in pre-TDN sEMG amplitude measurements between the intervention side and control side, $Z(39) = -1.17, p = 0.241$. However, there was a statistically significant difference in post-TDN sEMG amplitude measurements between the intervention side and control side in the SL0 position, $Z(39) = -3.08, p = 0.002$ with a medium effect size (Cohen’s $d = 0.74$). In the SLIR position, the difference between the intervention side and control side at pre-TDN and post-TDN was not statistically significant, $Z(39) = -0.27, p = 0.786$ and $Z(39) = -0.20, p = 0.042$, respectively.
Table 2. Descriptive statistics for demographic information of sample (n=39)

<table>
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<tr>
<th></th>
<th>Mean (SD)</th>
<th>Minimum</th>
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<tbody>
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<td>Age (years)</td>
<td>28.72 (5.47)</td>
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<td>41.00</td>
</tr>
<tr>
<td>Height (inches)</td>
<td>67.18 (3.76)</td>
<td>58.00</td>
<td>74.00</td>
</tr>
<tr>
<td>Weight (pounds)</td>
<td>167.67 (27.89)</td>
<td>107.00</td>
<td>232.00</td>
</tr>
<tr>
<td>Hours of weekly activity</td>
<td>7.00 (5.00)*</td>
<td>0.00</td>
<td>40.00</td>
</tr>
<tr>
<td>Number of trigger points</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.00 (1.00)*</td>
<td>3.00</td>
<td>8.00</td>
</tr>
<tr>
<td></td>
<td>4.97 (1.65)</td>
<td>2.00</td>
<td>9.00</td>
</tr>
<tr>
<td>Number of needles used</td>
<td>7.00 (2.00)*</td>
<td>5.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Level of soreness post TDN</td>
<td>3.00 (2.00)*†</td>
<td>0.00†</td>
<td>8.00†</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>16</td>
<td>41.03%</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>23</td>
<td>58.97%</td>
<td></td>
</tr>
<tr>
<td>Side of lower extremity dominance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>33</td>
<td>84.62%</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>6</td>
<td>15.38%</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: TDN = trigger point dry needling; SD = standard deviation
*Was not normally distributed. Results are reported as median and interquartile range
†Soreness was measured on a scale of 0 to 10
‡ Denotes the side that received TDN

Table 3. Descriptive statistics for HHD measurements, reported in kilograms

<table>
<thead>
<tr>
<th></th>
<th>SLO Position (n = 39)</th>
<th>SLIR Position (n = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Intervention*</td>
<td>Pre-TDN</td>
<td>Post-TDN</td>
</tr>
<tr>
<td>Control</td>
<td>Pre-TDN</td>
<td>Post-TDN</td>
</tr>
</tbody>
</table>

Abbreviations: HHD = hand held dynamometer; TDN = trigger point dry needling; SLO = side lying neutral position; SLIR = side lying internal rotation position
*Denotes the side that received TDN

DISCUSSION

The purpose of this study was to investigate whether the application of TDN to latent trigger points within the gluteus medius musculature affected strength measurements and muscle activation levels immediately following intervention. Participants within this study had to be asymptomatic to ensure that the latent trigger points themselves were the sole reason for muscle weakness, not pain or articular dysfunction. Furthermore, to specifically assess the effect that TDN had on strength measurements, it had to be completed in isolation of any other therapeutic intervention. As such, this is the first study to investigate the effects of TDN in isolation on strength measurements of the gluteus medius in asymptomatic individuals.

Results reported from previous research assessing the effect of TDN to latent trigger points in the gastrocnemius found no significant difference in strength measurements as measured by a HHD immediately following intervention. In contrast, participants within this study demonstrated a statistically significant increase in HHD measurements of gluteus medius force production immediately following the application of TDN in both testing positions. While the minimal clinically important difference for HHD measurements of the gluteus medius muscle has not been established, a large treatment effect size was found for interactions in the SLO position (partial eta squared = 0.74) and the SLIR position (partial eta squared = 0.71) following the application of TDN suggesting a strong relationship between intervention and the difference in HHD measurements over time as well as between groups. These results are consistent with previous studies that investigated immediate changes in force production of hip musculature measured by a HHD following the application of dry needling to MTrPs in the lower extremities for both symp-
tomatic and asymptomatic individuals when combined with other interventions.

Strength as measured by HHD force measurements was not the only outcome measure utilized in this study. Participants demonstrated a statistically significant decrease (78.17% of pre-TDN readings) in sEMG amplitude readings on the intervention side following the application of TDN even though HHD force measurements increased by 2.52 kg in the SLO position. While not statistically significant, sEMG amplitude readings in the SLIR position also decreased (90.52% of pre-TDN readings) on the intervention side, while HHD force measurements increased by 3.38 kg. Recorded sEMG amplitude readings can be used as a direct measure of the activation level of a muscle during a contraction. Both Dwyer et al. and Penney et al. found an increase in sEMG amplitude readings recorded during functional activities for individuals who demonstrated weakness of the gluteus medius muscle during baseline testing. These results suggest individuals who present with weakness of a muscle will require an increased level of muscle activation during a contraction, which may be a compensatory mechanism used to increase the amount of motor unit recruitment in order to achieve a given force output. As such, the inverse relationship of HHD force measurements and sEMG amplitude readings found in this study suggests a more efficient gluteus medius muscle contraction following the application of TDN, as participants required less motor unit recruitment to achieve greater levels of force production.

Based on the results of this study, latent trigger points can be identified as a potential source for impaired muscle function of the gluteus medius muscle resulting in a weak and inefficient muscle contraction. Authors of previous research have stressed the importance of eliciting a LTR during TDN to ensure that the myofascial needle has come in contact with a myofascial trigger point. While it is still unclear if the elicitation of one or multiple LTRs during the application of dry needleling is essential for reductions in pain and disability in various patient populations, the purpose of this study was to investigate the effects of TDN specifically to latent trigger points within the gluteus medius muscle. As such, it was critical that a LTR was elicited during the application of TDN to ensure that the needle had in fact come in contact with a latent trigger point. All of the study participants demonstrated a

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**Figure 5. Comparisons of HHD measurements prior to and following TDN**

Abbreviations: HHD = hand held dynamometer; SLO = side lying neutral; SLIR = side lying internal rotation; TDN = trigger point dry needling; kg = kilograms

**Table 4. Descriptive statistics for sEMG amplitude readings, reported in millivolts**

<table>
<thead>
<tr>
<th></th>
<th>SLO Position (n = 39)</th>
<th>SLIR Position (n = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median (IQR)</td>
<td>% MVIC</td>
</tr>
<tr>
<td><strong>Intervention</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-TDN</td>
<td>0.23 (0.19)</td>
<td>100%</td>
</tr>
<tr>
<td>Post-TDN</td>
<td>0.18 (0.15)</td>
<td>78.17%</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-TDN</td>
<td>0.24 (0.14)</td>
<td>100%</td>
</tr>
<tr>
<td>Post-TDN</td>
<td>0.23 (0.12)</td>
<td>95.89%</td>
</tr>
</tbody>
</table>

sEMG = surface electromyography; TDN = trigger point dry needling; MVIC = maximal volitional isometric contraction; IQR = interquartile range; SLO = side lying neutral position; SLIR = side lying internal rotation position

*Denotes the side that received TDN
palpable LTR and subjectively reported feeling a LTR during the application of TDN.

The exact mechanism of how TDN can reverse the effects of MTrPs is still unknown. Following the application of dry needling as well as the elicitation of a LTR, an increase in blood flow and subsequent tissue oxygenation have been found, along with a reduction of the biochemicals associated with pain and a localized muscle contraction within the milieu of a myofascial trigger point. Increases in localized blood flow and biochemical changes within the tissue itself may explain the increase in force production following the application of TDN observed during this study. Specifically, a reduction of calcitonin gene related peptide may allow for improved overlap of actin and myosin proteins through elimination of the localized muscle contraction which has the potential to improve cross bridge formation within the sarcomere unit, thereby improving muscle force production. Furthermore, Lucas argued that a reduction of group III and IV afferent input to second order neurons could potentially reverse alpha motor neuron inhibition, thereby improving neuromuscular control which may further explain the inverse relationship between HHD force measurements and sEMG amplitude readings found in this study following the application of TDN. Similarly, changes in neuromuscular function including a reduction in resting muscle tone as well as a decrease in muscle contraction time have been found following the elicitation of a LTR during the application of TDN to latent trigger points within the gastrocnemius.

An unexpected outcome of the study was that there was also a statistically significant difference in HHD measurements for the control side in the SL0 position as force measurements decreased by 1.31 kg. A possible explanation for this result could be found in the order in which the strength measurements were recorded and the level of soreness experienced following the application of TDN. Post-TDN strength assessments were completed first on the control side and then the intervention side. Participants reported an increased level of soreness in the gluteus medius muscle on the intervention side during the first MVC break test trial on their control side while in the SL0 position. Even though strength was being assessed on the control side, participants reported an increased level of soreness on the side that they were lying on potentially due to the need for stabilization during testing. Post needling soreness is commonly reported following the application of TDN and may have affected the participants’ ability to generate force during their first MVC break test trial on the control side in the SL0 position.

To support this explanation, post-TDN HHD force measurements of all three trials in the SL0 position on the control side were analyzed for differences. Significant differences for the measurements recorded between trial 1 and trial 2 and trial 1 and trial 3, while no significant difference was found between measurements recorded for trial 2 and trial 3. It is plausible that the level of soreness experienced in the gluteus medius musculature following the application of TDN reduced with each subsequent MVC break test trial. This phenomenon may explain why there was no significant difference found between measurements recorded for trial 2 and trial 3 in the SL0 position as well as no significant difference between any of the measurements recorded in the SLIR position on the control side, which were collected following the measurements in the SL0 position. Clinically, TDN is rarely performed in isolation and as such, clinicians should be aware of the possibility for post needling soreness and its potential effect on force production. Results of this analysis suggest that it may be beneficial to perform isolated gluteus medius contractions in an open chain position prior to any functional strengthening activities. This may reduce the effects that post-needling soreness may have on force production, thereby potentially reducing the risk for compensatory movement patterns during strengthening activities.
STUDY LIMITATIONS

The PI, who collected all of the data and applied the intervention to each of the study’s participants, was not blinded to which side received TDN and which side was the control. Even with standardized protocols, the risk of inadvertent bias during MVIC testing cannot be eliminated.

During the informed consent process, participants were instructed that the purpose of the study was to assess the effects of TDN on strength measurements of the gluteus medius, whether that be an increase or decrease in strength in an attempt to reduce the risk of performance bias. However, since participants were not blinded to which side received TDN and which side was the control side, performance bias cannot be completely ruled out.

Sham needles have been utilized in studies that have investigated the effects of dry needling to account for a potential placebo effect. When it comes to TDN studies, participants are able to feel the difference in needle depth penetration between the sham and TDN needles, as well as the elicitation of a LTR. Furthermore, if study participants have previously received TDN they may be able to realize the difference between the placebo and actual intervention. Future research on this topic could include other types of dry needling including superficial dry needling techniques, which may make it easier to include sham needles as a true placebo, while also reducing the potential for post needling soreness.

While the side of dominance was recorded for each of this study’s participants, it was not considered during statistical analysis outside of descriptive statistics for demographic information of the sample. Future studies may consider if side of dominance has an effect on the number of MTRPs found in the muscle tissue as well as study outcomes.

This study only assessed the outcome measures immediately following the application of TDN. Future studies should assess the effects of TDN on muscle strength at different post-treatment time intervals. Furthermore, TDN’s effect on muscle force production or activity during functional movements should also be investigated as this may have a more direct clinical application to improving performance during activities of daily living.

CONCLUSION

Application of TDN to latent trigger points within the gluteus medius musculature was able to significantly increase gluteus muscle force production immediately following intervention while reducing the level of electromyographic muscle activation required during force production testing. These results suggest that latent trigger points may have a negative impact on gluteus medius muscle strength as well as the efficiency of contraction. Clinically, latent trigger may be considered as a potential source of impaired muscle function.

CLINICAL TRIALS REGISTRATION NUMBER

ClinicalTrials.gov, ID NCT035802000

CONFLICTS OF INTEREST

The authors report no conflicts of interest

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44. Burden A. How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *J Electromyogr Kinesiol.* 2010;20(6):1023-1035. doi:10.1016/j.jelekin.2010.07.004


Background
Barriers and facilitators to research in sports medicine (SM) by physicians and allied health (AH) professions such as physical therapists and athletic trainers are understudied. The purpose of this research was to examine and compare research barriers, facilitators, and other research related facets including interests, comfort, knowledge, and resources among SM physicians and AH practitioners.

Study Design
Cross-sectional survey

Methods
The survey was sent to Pediatric Research in Sports Medicine (PRiSM) members. The survey was designed to ask respondents to identify their top barrier and facilitator to conducting research. Research interest (binary), self-rated comfort reading research articles (0-100 scale), self-rated knowledge conducting research independently (0-100 scale), and available research resources were evaluated. Descriptive statistics, chi-square, and t-tests were used to compare the responses between SM physicians and AH practitioners. The value of p<0.05 was set as a statistically significant criterion.

Results
The response rate was 55.7% (N=100). For both SM physicians and AH practitioners, the greatest research barrier was a lack of time. However, the leading research facilitators differed in the two professions. The top research facilitator for SM physicians was availability of research personnel, while availability of research mentoring was selected as a prime facilitator by AH practitioners. There were no differences in research interest between SM physicians (87.0%) and AH practitioners (95.5%, p=0.267). However, self-rated comfort reading research articles was higher in SM physicians (75.6±20.6) than AH practitioners (60.6±28.3, p=0.018). There were no differences in self-rated knowledge conducting research independently between SM physicians (70.2±18.6) and AH practitioners (65.4±24.6, p=0.163).

Conclusion
Lack of time was the top research barrier for both SM physicians and AH practitioners. Regarding research facilitators, having available time was the main facilitator for SM physicians while availability of mentoring was the leading facilitator in AH practitioners.

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Email: dai.sugimoto.007@gmail.com
Level of Evidence:

INTRODUCTION

Evidence-based practice (EBP) was developed with the aim to translate the most updated, appropriate evidence to clinical practices. The EBP model consists of three components: scientific evidence from empirical research, clinical experience of healthcare providers, and fundamental values of an individual patient. A combination of these three pillars is considered an important aspect in decision making. To enhance the EBP initiative, it was recommended to conduct research studies in the clinical setting where patients are present. Several studies reported positive clinical outcomes utilizing this approach. In this model, medical providers, also referred to as clinician-scientists, play an integral role as point personnel to translate research evidence to clinical practice. Although clinician-scientists are considered key personnel in the EBP model, they are also recognized as an "endangered species." According to Roberts et al., there has been a decrease in the number of clinician-scientists as well as reduction in the research activity time among physicians.

Several studies have been performed to identify reasons for the downward trend in research activities in clinician-scientists. According to the literature, a lack of available time, research knowledge, and administrative support were frequently reported. Additionally, some authors found that overall priorities for the research activities were different between physicians and allied healthcare (AH) practitioners. In summary, there are several known barriers to a clinician-scientist's participation in research and the perception of research activities differs between physicians and AH practitioners.

In contrast, factors that facilitate research activities are understudied compared to research barriers. Moreover, studies that focused on research barriers and facilitators specifically in the field of sports medicine (SM) are limited. Identifying barriers and facilitators to research is an important first step to help optimize the research engagement of clinician-scientists in the SM community. Furthermore, as previous research identified differences in research engagement between physicians and AH practitioners, it is important to examine the research barriers and facilitators between the two healthcare professions in SM community. Therefore, the purpose of this study was to examine and compare research barriers, facilitators, and other research related components including interests, comfort, knowledge, and resources among SM physicians and AH practitioners.

METHODS

STUDY DESIGN

A cross-sectional survey study design was employed. The recruitment strategy and the survey were reviewed and approved by the research ethics board of the host institution (Boston Children's Hospital) prior to the initiation of this study.

PROCEDURES

The survey, which consisted of research interests, perceptions, resources, barriers and facilitators, was developed by one clinician-scientist, a doctoral student, and a full-time researcher all who specialize in SM. The survey was reviewed by several SM physicians and AH practitioners prior to the dissemination. The survey was updated several times based on their feedback. The Pediatric Research in Sports Medicine (PRiSM) community was targeted as an initial source of participants to complete the survey. The main reason for selecting the PRiSM was that this organization is known as a multidisciplinary group in north America, mainly US, with members consisting of SM physicians (MD, DO) and SM specific AH practitioners including physical therapists (PTs) and athletic trainers (ATs). In this study, SM physicians were defined as those who held a Doctor of Medicine (MD) and/or a Doctor of Osteopathic Medicine (DO) degree, and individuals who held a physical therapy and/or athletic training license as AH practitioners. For analyses of the data from PRiSM members as a whole, all collected responses were included. For comparisons between SM physicians and AH practitioners, responses from those who did not have clinical duties, described as "others" were excluded from analyses.

Following approval from the PRiSM board, the on-line survey was disseminated to the PRiSM members via email in May 2020. To capture the survey responses, research electronic data capture (REDCap, Vanderbilt University, Nashville, TN, USA) was utilized. After an initial email, a total of three reminder emails were subsequently sent to the PRiSM members to encourage participation. All emails were sent from the PRiSM headquarters to ensure that the survey was only delivered to the PRiSM members. An access to the survey link was available for three months (closed in August 2020). The REDCap system was programmed to compute binary variables, multiple choices, and proportional ratios such as percentages (%).

Respondents were asked to identify and rank three barriers and three facilitators that contributed most to their participation in research activities from 10-11 distinctively unique choices. Additionally, respondents were instructed to rate each component of the 10-11 choices with four scales, 1) to no extent, 2) to a little extent, 3) to a moderate extent, and 4) to a great extent, and an option of no opinion/not applied. Respondents were asked whether they were interested in research or not with binary manner (yes or no), and for those who answered "yes," specific areas of research interests and actual research involvement were subsequently sought. Also, respondents were asked to give a self-rating of comfort reading research articles and their knowledge regarding conducting research independently with a 0-100 scale. For research resources, there were nine
choices including 1) graduate students, 2) facilities for research, 3) residents, 4) research coordinator, 5) research technician, 6) biostatistician, 7) statistical/analytical software, 8) none, and 9) other, and respondents were requested to pick available resources.

OUTCOME MEASURES

Primary outcome measures were barriers and facilitators of research activities. Secondary outcome measures were research interests, self-rated comfort reading research article, self-rated knowledge conducting research independently, and resources associated with research activities.

STATISTICAL ANALYSIS

Descriptive statistics including mean, standard deviation, and 95% confidence interval (95%CI) was used to analyze participants’ demographics. T-tests were used to compare continuous variables related to research perceptions between SM physicians and AH practitioners. Frequency of certain categories and ranks were expressed as percentages (%). For binary categorical variables such as research interests, 2 x 2 chi-square (X^2) analyses were employed to examine proportional differences between SM physicians and AH practitioners. The a priori statistical significance level was set as p<0.05 for all analyses. The top three parameters of the primary outcome variables, barriers and facilitators, were selected and stratified between SM physicians and AH practitioners. IBM SPSS statistical software (Version 26, SPSS Inc, Chicago, IL) was used for all analyses.

RESULTS

DEMOGRAPHICS

There were 100 responses (57 males and 39 females, missing sex responses: N=4). Response rate from PRIISM was 35.7%. Mean ages of participants were 42.5±10.7 (95%CI: 40.3, 44.7) years. Mean ages of males were 45.0±10.9 (95%CI: 42.1, 48.0) years, while females were slightly younger 38.9±9.5 (95%CI: 35.8, 42.0). About 86.6% of respondents reported spending 10 hours or more per week providing direct patient care. Also, 89.6% worked more than 15 hours per week at their primary medical care settings. Other demographics of the respondents including primary occupation, medical care settings, and geographic regions are presented in Table 1.

Furthermore, medical care settings of SM physicians and AH practitioners were examined. Medical care settings of SM physicians consisted of hospital (33.3%), hospital-based outpatient center (42.0%), private practice (15.9%), university (7.3%), and others (1.5%). Breakdown of care provision settings of AH practitioners were hospital (12.5%), hospital-based outpatient center (66.6%), university (12.5%), fitness center (4.2%), and others (4.2%).

BARRIERS AND FACILITATORS

Results of the 10-11 choices related to research barriers with the four rating scales were listed in Table 2.

Table 1. Characteristics of responders

<table>
<thead>
<tr>
<th>Professional Credentials:</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doctor of Medicine (MD)</td>
<td>3 (3.0%)</td>
</tr>
<tr>
<td>Doctor of Osteopathic Medicine (DO)</td>
<td>66 (66.0%)</td>
</tr>
<tr>
<td>Physical Therapy (PT)</td>
<td>17 (17.0%)</td>
</tr>
<tr>
<td>Athletic Trainer (AT)</td>
<td>7 (7.0%)</td>
</tr>
<tr>
<td>Other*</td>
<td>7 (7.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Primary Practice Settings:†</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital</td>
<td>26 (26.8%)</td>
</tr>
<tr>
<td>Hospital based outpatient center</td>
<td>45 (46.4%)</td>
</tr>
<tr>
<td>Private practice</td>
<td>11 (11.3%)</td>
</tr>
<tr>
<td>University</td>
<td>11 (11.3%)</td>
</tr>
<tr>
<td>School</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Fitness/Training facility</td>
<td>1 (1.0%)</td>
</tr>
<tr>
<td>Other</td>
<td>3 (3.1%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geographic Locations:‡</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Atlantic</td>
<td>4 (4.7%)</td>
</tr>
<tr>
<td>Mid-West</td>
<td>17 (19.8%)</td>
</tr>
<tr>
<td>North East</td>
<td>14 (16.3%)</td>
</tr>
<tr>
<td>North West</td>
<td>4 (4.7%)</td>
</tr>
<tr>
<td>South East</td>
<td>17 (19.7%)</td>
</tr>
<tr>
<td>South West</td>
<td>11 (12.8%)</td>
</tr>
<tr>
<td>West</td>
<td>13 (15.1%)</td>
</tr>
<tr>
<td>Others</td>
<td>6 (7.0%)</td>
</tr>
</tbody>
</table>

* Others: professional credentials of these individuals are PhD and MSc.
† Primary practice setting: three responses were missing.
‡ Geographic locations: fourteen responses were missing.

Among the 11 choices, the greatest barrier for research activity was a lack of time (28.3%). The research barriers were further stratified by SM physicians and AH practitioners. The top selection of the research barriers was the same between the two medical professions: a lack of time (Figures 1, 2). However, other reported barriers differed between SM physicians and AH practitioners (Figures 1, 2).

Similarly, 10 choices related to research facilitators were assessed by four rating scales and the outcomes were found in Table 3.

In the 10 choices, the leading research facilitator was available time (18.5%). Moreover, research facilitators were analyzed separately between SM physicians and AH practitioners (Figures 3, 4). The top research facilitator for SM physicians was availability of research personnel, while availability of research mentoring was selected as the top facilitator in AH practitioners (Figures 3, 4).

INTERESTS IN RESEARCH ACTIVITIES

About 88.7% of respondents expressed an interest in research, while 11.3% chose no research interest (missing responses, N=3). AH practitioners showed higher research interest (95.5%) compared with SM physicians (87.0%), but
Table 2. Ratings of research barriers

<table>
<thead>
<tr>
<th>Barriers and Facilitators of Research in Pediatric Sports Medicine Practitioners: A Survey of the PRiSM Society</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>1. As a clinician, I feel I do not have enough authority or ability to implement research into a clinical setting to improve patient care</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>2. Facilities</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>3. Coworkers and/or leadership is not supportive of research</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>4. Lack of perceived benefit to my own professional career</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>5. Limited or no funding</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>6. Limited access to a regulatory team</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>7. Limited access to research coordinator</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>8. Limited access to biostatistician</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>9. Difficulty recruiting participants</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>10. Lack of time</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
<tr>
<td>SM physicians</td>
</tr>
<tr>
<td>AH practitioners</td>
</tr>
<tr>
<td>11. Restrictive privacy law</td>
</tr>
<tr>
<td>To No Extent</td>
</tr>
<tr>
<td>Overall</td>
</tr>
</tbody>
</table>
To No Extent  | To a Little Extent  | To a Moderate Extent  | To a Great Extent  | No Opinion / Not Applied |
---|---|---|---|---|
SM physicians  | 21 (38.2%)  | 23 (41.8%)  | 6 (10.9%)  | 2 (3.6%)  | 3 (5.5%)  |
AH practitioners  | 8 (36.4%)  | 6 (27.3%)  | 5 (22.7%)  | 1 (4.5%)  | 2 (9.1%)  |

Note: Eighteen responses were missing overall (fourteen responses from SM physicians, two responses from AH practitioners, and two responses from others).

Figure 1. Research barriers of SM physicians.

Note: no SM physicians chose "As a clinician, I feel I do not have enough authority or ability to implement research into a clinical setting to improve patient care," "Limited access to a regulatory team," Difficulty recruiting participants," and "Restrictive privacy law."

Figure 2. Research barriers of AH practitioners.

Note: no AH practitioners selected "Limited access to a regulatory team," "Limited access to research coordinator," "Limited access to biostatisticians," "Restrictive privacy law," and "Other."
Table 3. Ratings of research facilitators

<table>
<thead>
<tr>
<th>1. Membership in professional organization(s)</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>3 (3.5%)</td>
<td>20 (23.5%)</td>
<td>29 (34.1%)</td>
<td>33 (38.8%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>1 (1.8%)</td>
<td>14 (24.6%)</td>
<td>18 (31.6%)</td>
<td>24 (42.1%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>5 (22.7%)</td>
<td>8 (36.4%)</td>
<td>8 (36.4%)</td>
<td>0 (0.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Participation in special research interest group(s)</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>1 (1.2%)</td>
<td>13 (15.3%)</td>
<td>22 (25.9%)</td>
<td>46 (54.1%)</td>
<td>3 (3.5%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>1 (1.8%)</td>
<td>6 (10.5%)</td>
<td>14 (24.6%)</td>
<td>34 (59.6%)</td>
<td>2 (3.5%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>0 (0.0%)</td>
<td>5 (22.7%)</td>
<td>6 (27.3%)</td>
<td>10 (45.5%)</td>
<td>1 (4.5%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Availability of research mentorship</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>0 (0.0%)</td>
<td>10 (11.8%)</td>
<td>30 (35.3%)</td>
<td>42 (49.4%)</td>
<td>3 (3.5%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>0 (0.0%)</td>
<td>6 (10.5%)</td>
<td>20 (35.1%)</td>
<td>29 (50.9%)</td>
<td>2 (3.5%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>0 (0.0%)</td>
<td>3 (13.6%)</td>
<td>8 (36.4%)</td>
<td>11 (50.0%)</td>
<td>0 (0.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Funding</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>5 (5.9%)</td>
<td>17 (20.0%)</td>
<td>22 (25.9%)</td>
<td>38 (44.7%)</td>
<td>3 (3.5%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>3 (5.3%)</td>
<td>13 (22.8%)</td>
<td>15 (26.3%)</td>
<td>24 (42.1%)</td>
<td>2 (3.5%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>4 (18.2%)</td>
<td>6 (27.3%)</td>
<td>11 (50.0%)</td>
<td>0 (0.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5. Support from leadership/colleagues</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>2 (2.4%)</td>
<td>4 (4.7%)</td>
<td>28 (32.9%)</td>
<td>48 (56.5%)</td>
<td>3 (3.5%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>1 (1.8%)</td>
<td>2 (3.5%)</td>
<td>22 (38.6%)</td>
<td>30 (52.6%)</td>
<td>2 (3.5%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>1 (4.5%)</td>
<td>6 (27.3%)</td>
<td>13 (59.1%)</td>
<td>1 (4.5%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. Available time</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>6 (7.1%)</td>
<td>13 (15.3%)</td>
<td>9 (10.6%)</td>
<td>55 (64.7%)</td>
<td>2 (2.4%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>4 (7.0%)</td>
<td>10 (17.5%)</td>
<td>5 (8.8%)</td>
<td>37 (64.9%)</td>
<td>1 (1.8%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>3 (13.6%)</td>
<td>3 (13.6%)</td>
<td>14 (63.6%)</td>
<td>1 (4.5%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. Research seen as beneficial to patient care</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>4 (4.7%)</td>
<td>5 (5.8%)</td>
<td>27 (31.8%)</td>
<td>45 (52.9%)</td>
<td>4 (4.7%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>2 (3.5%)</td>
<td>4 (7.0%)</td>
<td>17 (29.8%)</td>
<td>32 (56.1%)</td>
<td>2 (3.5%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>2 (9.1%)</td>
<td>5 (31.8%)</td>
<td>11 (50.0%)</td>
<td>1 (4.5%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. Research training and education</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>1 (1.2%)</td>
<td>12 (14.1%)</td>
<td>36 (42.3%)</td>
<td>36 (42.3%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>1 (1.8%)</td>
<td>8 (14.0%)</td>
<td>25 (43.9%)</td>
<td>23 (40.4%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>3 (13.6%)</td>
<td>9 (40.9%)</td>
<td>9 (40.9%)</td>
<td>0 (0.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. Access to research resource (equipment, laboratory, software, etc)</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>5 (5.9%)</td>
<td>16 (18.8%)</td>
<td>30 (35.3%)</td>
<td>34 (40.0%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>3 (5.3%)</td>
<td>14 (24.6%)</td>
<td>20 (35.1%)</td>
<td>20 (35.1%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>3 (13.6%)</td>
<td>8 (36.4%)</td>
<td>10 (45.5%)</td>
<td>0 (0.0%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10. Availability of research personnel (statisticians, research assistants, coordinators, etc)</th>
<th>To No Extent</th>
<th>To a Little Extent</th>
<th>To a Moderate Extent</th>
<th>To a Great Extent</th>
<th>No Opinion / Not Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>3 (3.5%)</td>
<td>15 (17.8%)</td>
<td>17 (20.0%)</td>
<td>47 (55.3%)</td>
<td>3 (3.5%)</td>
</tr>
<tr>
<td>SM physicians</td>
<td>2 (3.5%)</td>
<td>8 (14.0%)</td>
<td>9 (15.8%)</td>
<td>36 (63.2%)</td>
<td>2 (3.5%)</td>
</tr>
<tr>
<td>AH practitioners</td>
<td>1 (4.5%)</td>
<td>4 (18.2%)</td>
<td>7 (31.8%)</td>
<td>9 (40.9%)</td>
<td>1 (4.5%)</td>
</tr>
</tbody>
</table>

Note: Fifteen responses were missing from overall (twelve responses from SM physicians, two responses from AH practitioners, and one response from others).

This difference was not statistically significant (p=0.267). The specific areas of research interests were presented in Table 4. Additionally, actual research involvement is also displayed in Table 4.
COMFORT, KNOWLEDGE, AND RESOURCES

Regarding self-rated comfort in reading research articles, overall mean was 72.0±23.6 (95%CI: 67.2, 76.8) using a 0-100 scale (missing responses, N=5). In comparison between SM physicians and AH practitioners, the mean value was higher in SM physicians [75.6±20.6 (95%CI: 70.6, 80.6)] compared with AH practitioners [60.6±28.3 (95%CI: 47.0, 74.5)] (p=0.018). Additionally, overall mean score of self-rated knowledge regarding conducting a research study independently was 68.4±20.5 (95%CI: 64.2, 72.5) using a 0-100 scale (missing responses, N=6). The mean value of the self-rated knowledge conducting research in SM physicians was 70.2±18.6 (95%CI: 65.7, 74.7), while AH practitioners demonstrated a score of 63.4±24.6 (95%CI: 51.5, 75.2) (p=0.163). Available resources to perform research activities as a whole and by each profession are shown in Table 5.

DISCUSSION

The current study investigated barriers and facilitators to research, as well as other research related components including interests, comfort, knowledge, and resources among SM physicians and AH practitioners. According to
our data, both SM physicians and AH practitioners identified a lack of time as the top barrier to research participation (Figures 1, 2). However, the remaining top research barriers were different between the two professions. The second and third most common research barrier identified from SM physicians were limited access to a research coordinator and having co-workers or leadership that is not supportive of research. This finding indicated the importance, for SM physicians, of having access to valuable research staff as well as support from peers and leadership. Conversely, the second and third barriers in AH practitioners were apparently related to a negative mindset/outlook toward research.

AH practitioners who participated in the current study were PTs and ATs. Since investigations related to research barriers and facilitators of PTs and ATs were understudied, available studies related to another group of AH practitioners, nurses, were synthesized.16–19 A few studies indicated
that the negative mindset/outlook toward research activities may stem from a clinical hierarchy between physicians and nurses.\textsuperscript{16–18} The authors of these studies described that nurses were not ranked or positioned to change clinical practices within the clinical setting.\textsuperscript{16–18} They postulated that a lack of autonomy in the clinical setting may negatively influence research interests and activities.\textsuperscript{16,18,19} This description aligns well with the current study findings (Figure 2). About 11% of respondents from the AH practitioners in the current study showed disbelief and/or doubt of having enough authority or ability to implement research into a clinical setting to improve patient care. Additionally, another 11% of respondents from the AH practitioners did not perceive research as being beneficial to their own professional career. This may be related to another barrier, coworkers and/or leadership is not supportive of research, among the AH practitioners (6%). In fact, one study discussed that an underlying major research barrier was a lack of research support from leadership.\textsuperscript{3} This lack of research support from leadership stemmed from the culture of the AH practitioners work environment.\textsuperscript{3} According to this report,\textsuperscript{5} direct patient care is usually perceived as a primary responsibility, and research activity was often viewed as secondary or as a non-essential task in AH practitioners.\textsuperscript{3} The primary job of both PTs and ATs is, indeed, direct patient care, and therefore, if research is perceived as a non-essential task, this will likely contribute to the perceived lack of benefit that PTs and ATs feel toward spending time engaging in research activities.

Research facilitators were distinctively different and unique in each profession (Figure 3, 4). Among SM physicians, availability of research personnel was the top facilitator (25%) followed by available time (21%). Underlying reasons of these facilitators may stem from a special role a few SM physicians often take. One unique role of SM physicians is to work as a local sports team doctor.\textsuperscript{20,21} The responsibility of working as a team doctor is considerably comprehensive, especially for a collision sport such as American football,\textsuperscript{22,23} and for some high-profile teams, traveling with the team is also a part of the job.\textsuperscript{24} In short, serving a team physician to local sports teams is a time-consuming commitment, which explains the reason why availability of research personnel to facilitate research activities is extremely important. Furthermore, SM physicians reported being more comfortable reading research articles than AH professionals and reported a higher self-perceived ability to conduct research independently (although not statistically different) as compared to AH practitioners. Therefore, having access to available research personnel may be a key factor to the promotion of research activities within their limited time.

Unlike selections of SM physicians, availability of research mentoring (32%) and support from leadership/colleagues (26%) were chosen as leading facilitators from AH practitioners. The importance of available time as a research facilitator has been previously documented by various authors.\textsuperscript{3,25–27} However, the availability of mentoring and support from leadership/colleagues as primary facilitators expressed by PTs and ATs has not been previously reported. This alone is an important finding to highlight, indicating the current lack of mentorship or support from leadership among AH professionals. This concept should be considered moving forward when evaluating and discussing barriers and facilitators in SM research. Yet, it is essential to recognize that this finding may also be unique to the field of SM, given the prevalence of PTs and ATs in this community. Furthermore, although not statistically significantly different, AH practitioners showed greater research interests (95.5%) than SM physicians (87.0%), especially with regards to research design/protocol development and data collections, while having less access to a research technician and a biostatistician. These findings emphasize the importance of providing support to further facilitate research activities in AH professionals.

A potential solution to overcome the identified barriers and nurture the facilitators may be to develop those who have a role as researcher associates. In this study, 7% of the survey respondents did not have clinical duties and were labeled "others", and their primary responsibilities were associated with research activities. Since a lack of time was the top barrier for both SM physicians and AH practitioners, collaborating with research associates (others) may help save time and facilitate participation. For instance, pivotal research activities such as preparing IRB documents, analyzing collected data, and drafting scientific manuscripts often take substantial time. However, research associates may be able to optimize these steps and shorten the time in each step. Additionally, availability of research personnel was found as a leading facilitator in SM physicians, and research associates are an ideal candidate to fill their needs. Furthermore, availability of research mentoring was selected as the greatest facilitator in AH practitioners. Developing a mentor-mentee relationship with established researchers may help enhance research productivity of AH practitioners. In summary, leadership and/or administrators should investigate promoting and solidifying a collaborative relationship among SM physicians, AH practitioners, and research associates.

LIMITATIONS

Several limitations need to be stated, with a main limitation being that the current study data were obtained solely from the PRiSM membership. Clinicians and practitioners who are in societies such as PRiSM, are likely to already have positive perspectives on research, and thus introduce a potential bias in the study findings, especially as involvement is typically on a volunteer basis. Regardless, this preliminary assessment into barriers and facilitators is an important first step in capturing the current state of research participation among members in the SM community. Furthermore, although the current study had acceptable response rate (35.7%), an overall number of survey respondents was 100, which is a relatively small sample size. Also, nearly all members were geographically located in the US and Canada. Thus, the results may not be generalized to other regions or continents of SM physicians and AH practitioners. Additionally, responses from AH practitioners (24%) were lower than SM physicians (69%). More-
over, approximately 9% of respondents had additional degrees such as a Doctor of Philosophy (PhD), Masters of Public Health (MPH), and Masters of Science (MSc). Some respondents may be using those degrees as their primary responsibility/function in their institutions. Lastly, the survey was programmed to be sent to each of the PRiSM members only once. To avoid confusion and errors, the survey was directly delivered from the PRiSM headquarters to all PRiSM members. The collected responses were rigorously checked. However, the possibility of responses from non-members and potential duplicates (multiple responses from one member) could not be eliminated.

CONCLUSION

The results of this study indicate that a lack of time was the top research barrier for both SM physicians and AH practitioners. Research facilitators were different between SM physicians and AH practitioners. Having available personnel was the main facilitator for SM physicians, while availability of mentoring was the leading facilitator in AH practitioners. Those who take a leadership position in a SM department may need to be aware these findings, especially if enhancement of research productivity is priority. Future studies are warranted to investigate other parameters to optimize evidence-based practices.

DISCLOSURE OF FUNDING SOURCE

None

CONFLICT OF INTEREST

All authors have no conflict of interest to disclose.

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REFERENCES


Appendix 1

Case Reports

Progressive Loading in a Strongman Following Distal Biceps Repair: Re-Thinking Load Progression – A Case Report

Daniel Lorenz, DPT, PT, ATC, CSCS

1 Physical Therapy, Lawrence Memorial Hospital/OrthoKansas

Keywords: distal biceps rupture, shared decision making strongman, blood flow restriction, ischemic preconditioning

https://doi.org/10.26603/001c.39796

International Journal of Sports Physical Therapy

Background
Rupture of the distal biceps is relatively rare and post-operative protocols are typically vague and are used on many patients, regardless of pre-morbid status. The primary objective is to share the progressive loading strategy used in the rehabilitation of a strongman athlete following a surgical repair of the distal biceps. An additional objective is to highlight the need for individualized protocols and progressions with respect to patient goals and sport demands, as well as the need for shared decision making (SDM) between the medical doctor, patient, and rehabilitation provider.

Case Presentation
The subject is a 39-year-old strong man competitor who suffered a distal biceps rupture while doing a tire flip during training. After having it repaired, the post-operative recovery was unremarkable. The focus of the described intervention was establishing load during rehabilitation exercises that were unique to this individual based on his pre-morbid level of strength and training history as well as the unique demands of his sport.

Outcomes
The patient achieved symmetrical isokinetic strength of the elbow flexors at 60°/second in supine at six months post-operative.

Discussion
The case highlights a successful outcome in a strongman competitor with a distal biceps rupture repair. Typically, protocols are vague and lack specific standards for establishment of load for exercises. Often starting points and progressions are arbitrary and lack rationale tailored to individual needs and/or pre-morbid status. The case offers a framework for establishing and progressing load while also discussing how a shared decision-making model can lead to positive outcomes.

INTRODUCTION
Avulsion of the distal biceps brachii tendon represents about 3% of bicep tendon injuries.1 The typical mechanism of these injuries occurs in a flexed elbow and supinated forearm position,1,2 which may be associated with acute tensile overload.3 Patients frequently report a history of an audible pop and acute pain at the antebrachial fossa after an eccentric contraction of the biceps caused by unexpected extension force applied to a flexed elbow with the forearm in a supinated position.3,4 The majority of patients with distal bicep tendon ruptures are males in the fourth to fifth decade of life, and 52-86% occur in their dominant extremity.2,5,6 Common risk factors include increased body mass index (BMI), use of anabolic steroids, smoking, weightlifting, and bodybuilding.1,4–7 Distal biceps rupture (DBR) can result in functionally significant loss of supination and elbow flexion strength, as well as decreased resistance to...
fatigue.\textsuperscript{1–8} Immediate surgical repair is the recommended course of treatment, but delaying surgery for a few weeks after diagnosis has been found to be equally beneficial compared to patients who have early surgical intervention within a week of injury.\textsuperscript{9} In other words, immediate repair is advocated in ideal circumstances but a short delay may not necessarily lead to worse outcomes.

Strongman is a competitive sport where athletes perform a variety of tasks with very high loads to test physical strength and stamina. The first World’s Strongest Man competition took place in 1977. Most strongman competitions consist of six to eight events. Contestants are awarded points for each event based on their position in stand-\textsuperscript{ings}.\textsuperscript{10} Strongman competitions typically have four key components – the overhead or push press, the deadlift, grip strength, and anaerobic capacity.\textsuperscript{11} Strongman has some nuances in competition compared to other weightlifting sports. Contrary to powerlifting and weightlifting where only a loaded bar is used, strongman events often have implements like logs (Figure 1), atlas stones (Figure 2), axles, sandbags, or devices that allow high loads to be carried over distances, like the farmer’s walk (Figure 3) or the yoke walk (Figure 4). Tire flips (Figure 5) and pushing/pulling high loads like sleds, vehicles or trucks (Figure 6) or sustaining isometric contractions with high loads such as the "Hercules Hold" (Figure 7) are also often a part of strongman competitions. Strongman competitors face a high relative risk of bicep injury due to their body mass coupled with lifting high loads.

Among strongman competitors, in a retrospective re-\textsuperscript{view}\textsuperscript{12} of 213 strongman athletes, 82\% reported injuries. Most (24\%) common were in the low back, followed by bicep and knee (11\% each), with most being strains of muscle (38\%) and tendon (23\%). 68\% of the injuries were acute.\textsuperscript{12}

There were significantly more competition injuries for those under 30 years of age compared to those over the age of 30.\textsuperscript{12} Training with implements almost doubled the injuries compared to traditional weight training methods using barbells, dumbbells, or universal weight training ma-\textsuperscript{chines}.\textsuperscript{12} Ninety-one percent of those injured sustained injuries when lifting loads 90\% of 1RM or greater. The incidence of bicep injury in the strongman athlete was higher than for weightlifting,\textsuperscript{13} powerlifting,\textsuperscript{13,14} and bodybuilding.\textsuperscript{15} Events like the tire flip and stone lifts suggest that bicep weakness or fatigue may limit the transfer of force produced from the larger muscle groups about the shoulder and torso and increase bicep injury risk.\textsuperscript{12} Deadlifting has also been implicated as a mechanism of bicep rupture. A study evaluating mechanisms of distal bicep found that all ruptures occurred in the supinated arm in “mixed grip” lifters when the elbow was in extension (“mixed grip” is when one hand is supinated and the other is pronated). As such, researchers proposed that eccentric loading on an ex-\textsuperscript{tended and supinated elbow may be an alternative mecha-\textsuperscript{nism of injury}.\textsuperscript{4}
Due to the nature of the sport, the extreme loads lifted, as well as the pre-morbid strength levels of these athletes, adjusting rehabilitation protocols to accommodate the physical capabilities of the athlete is warranted. Alternatively, there may be implications for healing rate and strength of repair due to pre-morbid status. A published post-operative protocol limited loading to 5-10 pounds for the first several weeks and limited biceps isotonics till 12 weeks, but protocols vary among surgeons. The reattachment site is at the greatest risk for failure during the first one to two weeks after surgery. Normal tension of the bicep with the elbow at 90° against gravity is about 50 Newtons. Mazzocca et al. evaluated four different distal bicep repair techniques and cyclical load to failure varied from 232 Newtons to 440 Newtons. Kettler and others evaluated the linear load to failure strength of thirteen different methods for distal biceps tendon repair and found that the EndoButton had a significantly higher failure load than other techniques (259 +/- 28 N), with a mean failure rate of 180 N among all methods. The transosseous suture technique, used for the subject in this case, showed a mean failure of 210 +/- 29 N. In Kettler et al., no tendon failure was seen in any transosseous or suture anchor repair when using an Ethibond No. 2 suture. Of note, the subject in this case was fixated with FiberWire, rather than Ethibond. A previous study by Miller et al. comparing orthopedic sutures found that FiberWire had higher ultimate load to failure and resisted the greatest number of cycles to failure compared to Ethibond and other suture types. The clinical utility of cadaveric study information is questionable however because the Mazzocca et al. study was in "much older" elbows with low bone density and it included cyclic loading at 3600 cycles with 50 Newtons. In contrast, the Kettler et al. study was linear load to failure, but also in cadaveric elbows with an age range of 79 +/- 15 years. Older, cadaveric elbows with low bone density are arguably not a proper comparison with the patient in this case.

From a rehabilitation perspective, it has been suggested that unrestricted or early range of motion may begin earlier since repair strength is greater than the force of an unweighted forearm in a splint or brace. Restrictions typ-
ically include lifting no more than five pounds and no supination against resistance. At six weeks, gradual strengthening of the upper extremity and aerobic conditioning may begin.\textsuperscript{8} Strength training commences usually about two to three months post-operative.\textsuperscript{22} Return to heavy lifting is allowed at three to six months after surgery. The reader is referred to rehabilitation plans that have been outlined previously.\textsuperscript{23–25}

Given that each patient’s demands are unique, should this same loading restriction in the initial phases be used for a strongman as it would be for a recreational athlete? In Srinivasan et al.,\textsuperscript{8} return to heavy lifting is suggested at three to six months after surgery. What defines “heavy?” A heavy load for one patient may be maximal for another, and a general warm-up for yet another. Therefore, the purpose of this case report is twofold. The primary objective of this case report is to share the progressive loading strategy used in the rehabilitation of a strongman athlete following a DBR repair. An additional objective is to highlight the need for individualized protocols and progressions with respect to patient goals and sport demands, as well as the need for shared decision making (SDM) between the medical doctor, patient, and rehabilitation provider.\textsuperscript{24}

**CASE DESCRIPTION**

The subject (age = 39 years old, height= 187 cm, weight= 125kg) is a right-hand dominant male who ruptured his right distal bicep tendon doing a tire flip. The subject underwent successful surgical repair (DBR) approximately 14 days later. Post-operatively, he was placed in a splint at 90° flexion with the forearm supinated. Per the physician protocol for this subject, the first two weeks required the elbow brace to be locked at 90° when not performing rehabilitation activities. Exercises included elbow extension to 45° with the forearm supinated, passive bicep flexion to tolerance, passive forearm pronation and supination with the elbow flexed to 90°, and maintenance of range of motion of the shoulder, wrist, and hand. From two to six weeks post-operative, the elbow brace was to remain locked at 90° when not doing rehabilitation exercises. Exercises during this time frame included elbow active extension and passive flexion. Extension was allowed to be increased by 15° per week. While braced, the protocol advised light progressive resistance exercise for the musculature of the shoulder and grip strength exercises, but no active or resisted biceps work. From weeks six to eight, he was to wean from the brace and begin active elbow flexion without resistance. If needed, more aggressive treatments to get full extension could be utilized. From weeks 8-12, resisted bicep isotonic exercises could be initiated, and at twelve weeks post-operative, the protocol indicated that sport-specific activities could commence.

The subject’s first physical therapy visit was approximately three weeks post-operatively. The subject presented to physical therapy with his brace at 90° flexion. The wound was healed, wrist and hand motion were symmetrical and pain free. Left elbow range of motion was 0-150°, while the right was 11-142° passively (note, lacking 11 degrees from full extension). There were no other objective measures performed on this date because a lengthy discussion commenced about his displeasure with what he felt was a generic protocol that didn’t suit his needs. He felt that he should not be doing the same protocol as the typical patient would. The subject was very frustrated with his medical provider and the lack of guidance he received, and he was dismayed by the fact that the protocol read “updated in 2015,” about six years before his injury. Further, he felt like advances had to have been made since then. He struggled with compliance as he believed there had to be more current knowledge and subsequently adjustments or updates to treatment protocols. As the discussion progressed, he revealed that he was doing some active flexion out of his brace in the early phases and had not been very compliant with his brace. The subject was educated on the need for compliance with brace use and avoiding active flexion range of motion to protect his repair and healing until told otherwise. The potential adverse effects of non-compliance were highlighted by discussing graft failure. The physical therapist also talked about long-term planning and goals and a timeline was discussed for getting back into his desired level of high loading activities necessary for training for strongman events. The physical therapist also made it clear that in order to continue working together, there had to be some mutual respect and compromise on progression of activities.

On the second visit three days later, gentle isometrics of the bicep at 90° flexion using two-fingers of resistance mid-forearm and multi-angle tricep isometrics were initiated. Even though the protocol at the time called for no active bicep work, gentle two-finger isometrics with a short lever arm at mid forearm was used due to the patient’s pre-morbid status and to retard muscle atrophy.

Blood flow restriction (BFR) training (Delfi Medical, Vancouver, BC) with supine tricep extension to 30° of extension utilizing a resistance band was performed to help accommodate the subject’s desire to “somehow get some arm work in.” He was pre-occupied with the level of atrophy compared to his uninolved arm already. Given the subject’s typical workout routine and level of effort he was accustomed to, BFR to the triceps was a reasonable compromise to simultaneously protect the repair and potentially provide some psychological benefit to the patient by enhancing low-load training. BFR is a training modality that utilizes low loads to promote hypertrophy and strength gains in muscle when higher loads are not appropriate.\textsuperscript{26} Sessions closed with neuromuscular electrical stimulation (NMES) to the bicep with the arm resting at his side in approximately 90° flexion, followed by ischemic preconditioning (IPC) to the involved arm inferior to the deltoid tuberosity. Contrary to BFR being performed with exercise at a percentage of arterial occlusion pressure for three to five sets of an exercise, IPC is performed with full occlusion at rest for three to five minutes followed by reperfusion for three to five minutes, and this cycle is repeated three times. IPC has been shown to increase muscle perfusion,\textsuperscript{27,28} oxygen uptake and force in strength-trained athletes,\textsuperscript{26,27} increase microvascular blood flow,\textsuperscript{28} provide an ergogenic
benefit,29 increase muscle performance when performed prior to resistance training,30 and help with recovery.31 IPC was used in this case after the session to potentially help with recovery and the muscle physiology benefits listed above, but also to maximize individualized patient care time. While the benefit of IPC for this subject is debatable, he was grateful for the progressive approach to his rehabilitation that went beyond the general protocol. For his home program, he was also encouraged to perform high-load isolated biceps isotonics to his uninvolved side to potentially realize the benefit of cross-education. Cross-education is the use of unilateral resistance training to increase the strength of the contralateral non-trained side.32 Sato et al.32 found that progressive eccentric or concentric elbow flexor activity performed twice a week for five weeks showed strong cross-education effects on involved side maximum voluntary isometric contraction (MVIC) and one-repetition maximum (IRM).

The subject was seen only once a week due to his schedule and the distance he travelled for his appointments. Sessions involved soft tissue and scar mobilization, passive range of motion, elbow joint mobilizations, isometrics, and exercises and modalities described previously. At week six, despite the initial protocol limiting resisted bicep activities till eight weeks, he was cleared by his physician to begin resisted exercise at week six with a five-pound restriction and was “released to his PT.” The physical therapist was unable to reach the provider for confirmation. The subject was again frustrated by the minimal guidance received by his medical provider, stating that he was only told not to “go too heavy too fast.” For this subject in particular, “too heavy” for him would far exceed a maximal attempt for a typical patient. For rehabilitation professionals in a number of settings, there is a delicate balance between tailoring protocols to individual histories and physical qualities prior to injury or surgery and respecting the healing process. Arbitrary guidelines are provided (such as the statement above) with no sound progression or template for patients or their rehabilitation providers.

At this physical therapy visit, the subject’s range of motion was 2-141° actively, and 0-145° passively. Bicep strength was measured with a hand-held dynamometer (HHD) in sitting with elbow flexed to 90°. The subject was instructed to push to comfort without pain or pulling sensation over the repair site. Testing consisted of three, five-second flexion tests against a rigid dynamometer placed in his hand. His uninvolved side averaged 48 pounds while the involved side averaged 26 pounds. The rationale for performing HHD testing at 90° because the bicep is more vulnerable the closer the lifting load is to extension based on previously discussed mechanisms of injury. The test was not intended to be a maximum force assessment but rather a test of force to tolerance without pain. Interestingly, the uninvolved side values seemed rather low given his pre-morbid status. These lower-than-expected values may be due to the position of the elbow during testing or a decline in strength due to limited resistance training of the uninvolved side since the surgery. At this time frame, sled pushes were added with the elbow was locked in extension and the movement was driven by the legs. Additionally, isometric mid-thigh pull (IMTP) (Figure 8) was added with the involved side in pronation due to previous studies showing the supinated grip position has been implicated in DBR.4 The IMTP is a useful exercise in rehabilitation because it has been correlated to athletic capabilities of strength, maximal sprint speed, countermovement jump, and change of direction tests.33–35

Bench press as well as barbell military press were initiated at six weeks post-op due to the subject’s previous experience and desired goals as well as the limited involvement of the bicep in these activities. Saeterbakken and colleagues56 previously found that that flat bench press resulted in 48.3%-68.7% less bicep activity than incline bench position and that a narrow grip (biacromial distance) elicited lower bicep loads than a wide grip (50% more than biacromial distance). For the military press, Saeterbakken and Finland57 found similar EMG of the biceps during seated barbell and dumbbell shoulder press, and about 16% greater bicep activation in standing barbell versus dumbbell shoulder presses. Loads used were either 30% of previous one-repetition maximum (1RM), 30% bodyweight, or comfort, whichever came first. The American College of Sports Medicine (ACSM) has previously stated38 that for muscular endurance training, the loads should be about 50% of 1RM and this was supported by Schoenfeld et al.39 in a later review. These guidelines are in the healthy general population. 30% was used because it is about half of the load used in the healthy population as suggested by the ACSM.38 The rationale here was to establish a load that was pain-free and that the subject felt comfortable/confident with while facilitating proper technique. For this subject, previous best on the bench press was close to 400 pounds. He worked up to 185 pounds on the first day after initial sets.

Figure 8. Isometric Mid-Thigh Pull
of five repetitions each at 95, 135, and 165 pounds. Previous military press 1RM was 270 pounds, and the subject worked up to 95 pounds in the first training session. Given the subject's extensive training experience, he was given the freedom to load within a subjectively comfortable range on these specific lifts with the guidelines of limiting to no more than 50% of previous 1RM. This approach allowed the subject to have input into his progression limited by his subjective analysis of limb confidence, comfort, and pain or pulling sensation at the distal bicep during the lifts (had to be absent). It was theorized that using pain, a subjective increase in "pulling sensation" at the location of the repair, or breakdown in exercise technique would be an adequate clinical basis for judgment of load tolerance. In this case, the subject's pre-morbid status along with surrounding healthy tissue stress shielding the bicep as well as these being multi-joint, total body lifts made this a plausible guideline. Additionally, almost all the exercises performed were not bicep exercises in isolation or where the bicep is the prime mover, as would be the case in bicep curls or pull-ups. In the exercises performed, the biceps acted as stabilizers or synergists.

When isolated bicep isotonics commenced at week six, BFR was used due to the ability to improve strength and hypertrophy with low loads. The use of BFR enabled the physical therapist to load the bicep in isolation but mitigating risk of injury by using heavier loads without BFR. An initial load of five pounds was used due to it being the physician recommendation. The subject performed the suggested repetition scheme of 30/15/15/15 with 45 seconds rest between sets and the cuff remaining inflated. If the subject did not achieve failure or close to it on the final set, weight was increased one to two pounds for subsequent sessions.

At week eight, seated rows with a pronated grip were added, along with hammer curls using a rope with the forearm pronated at the start and ending the concentric phase in a neutral forearm position. Barbell snatch was also added at 30% of previous military press best. Chen and others found that bicep activity in the snatch increases with greater loads and velocities. Olympic lifts are typically performed at maximal velocities. Due to the low loads for this subject and low speed/effort of performance, it was not expected that the bicep load would be too high for this point in time.

From weeks 10–12, a neutral forearm grip was used for all lifts including seated rows, trap bar deadlifts, and hammer curls, for example. The subject's previous 1RM on the straight-bar deadlift was 900 lbs. Load was established to 30% of that for the first day, up to 270 lbs. At week 12, a supinated grip was used for more exercises, including the deadlift. Additionally, a front dumbbell carry was added to the routine, similar to the atlas stone carry position. His involved side HHD at 90° flexion averaged 46 pounds of force and 67 pounds on the uninvolved at the twelve-week assessment. Based on these HHD values, a 55-pound dumbbell was used as his target starting load due to the shared bilateral bicep load for the exercise and was increased 10% till the subject felt the load was comfortable. Also at 12 weeks, farmer walks with a trap bar were added. The farmer walk load commenced up to 30% of previous deadlift best. For all lifts, load was increased 20% per week as tolerated. Interestingly, the subject inquired about doing pull-ups at a previous visit and was advised against doing so, then came to his following visit with studies showing very high bicep EMG activity during pull-ups. These were avoided at this time. The reader is referred to Table 1 for the exercise grip progression used in this case.

<table>
<thead>
<tr>
<th>Grip Progression for Weight Training</th>
<th>Post-Operative Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Involved side pronated</td>
<td>8-10</td>
</tr>
<tr>
<td>Neutral</td>
<td>10-12</td>
</tr>
<tr>
<td>Involved side supinated</td>
<td>12+</td>
</tr>
</tbody>
</table>

OUTCOME

At 16 weeks, the first isokinetic test was performed in supine and he had an 11% deficit at 60°/second in elbow flexion. It was performed at this point due to the subject having approximately eight weeks of strength training completed. On his 15th visit at six months post-op, his isokinetic testing was symmetrical and he was released to resume training as tolerated with the addition of implements and he was cleared for progression to pull-ups at this time, starting with assisted pull-ups using elastic bands. The subject was strongly advised to obtain full clearance from his physician.

DISCUSSION

This case highlights two primary concerns in establishing resistance with load in the post-operative patient. First of all, this case highlights the call for medical and rehabilitation professionals to be more specific regarding progressions and loading rather than speaking in vague descriptions such as "don't go to heavy," "don't go too fast," "don't push it," "go slowly," or "resume heavy lifting." Obviously, these statements are non-specific and are entirely subjective. Furthermore, they provide no structure for decisions to be made by patients or rehabilitation providers. Complicating this are varying personality types and degrees of motivation. Any of the above statements could be interpreted completely different by two different patients.

There are established interval return to sport programs for a number of different sports that outline both volume and intensity progressions, but there is little guidance for medical or rehabilitation professionals on what best practices are regarding establishing the proper load for individual patients based on their injury, surgical intervention, and prior experience. Establishing load is often arbitrary or a "best guess," and often lacks precision regarding loading for each patient specifically. Complicating matters further
is the lack of data on ultimate load to failure on repaired or reconstructed tissues in non-cadaveric subjects. Because of that, extrapolating this information to patients is highly questionable.

Secondly, the case presents various potential methods to establish resistance including based on a percentage of bodyweight, a percentage of previously known 1RM, or a percentage of HHD values when appropriate. Subjective reports of pain, atypical feelings at the repair site, or breakdown in exercise technique may also help the rehabilitation provider in establishment of appropriate load. The subject in this case was accustomed to lifting extremely high loads, atypical for a great majority of patients.

The author proposes starting loads be at 30% of known previous 1RM or 30% of bodyweight with the understanding that the patient can load comfortably and with no pain or apprehension for multi-joint lifts. For isolated, single joint movements, it is suggested that the subject begin with 20-30% of their average HHD value for that exercise. Warm-up sets with up to five repetitions leading up to the target weight can be utilized for familiarization and instilling confidence. Certainly, if pain or discomfort occurs prior to achieving the 30% goal with the first few months, no further progression would be advised. Pain or discomfort may be more acceptable in later stages once equal strength has been achieved or it is short-lived and decreases and/or is eliminated after five to six repetitions are completed.

Furthermore, due to the subject’s experience lifting in this case, he had a good “feel” for the weight and safety in execution of the lift. He was provided guidelines to work within and complied with them. Once the loads were established on core lifts, load was increased about 20% per week.

Previous guidelines from the ACSM have established a 2-10% increase between sessions in the same week if the individual can perform the current workload for one to two repetitions over the desired number on two consecutive training sessions. Given the subject’s pre-morbid status, up to 20% was a reasonable target increase with the ability to adjust based on specific lifts and subjective comfort with the load prescribed.

Obviously in this case, the pre-morbid loads this subject lifted far exceeded what a majority of patients could lift safely. Two hundred seventy pounds on a deadlift for the first day might be a maximal attempt for some patients, but in this case, it was a weight that was easily lifted for him. The deadlift is primarily lifted with the legs and the biceps are isometrically contracted. This case highlights the need to be more individualized in loading progressions as well as establishing resistance for a given session. To the author, using 50% of the suggested loads in the healthy population was a reasonable anchor to begin with. Without establishment of appropriate loading, there is an opportunity cost to the subject in losing valuable sessions with under-loading. In other words, why lift in three or four weeks what can be lifted today safely and appropriately?

This case also highlights how shared decision making can be used during rehabilitation planning. While the effect of shared decision making (SDM) on the outcome in this case is not known, the subject’s confidence in the physical therapist and his optimism on the course of treatment likely changed for the better once the rules were established but his previous lifts and experience were considered in the progressions. Plus, more modern modalities such BFR and were well-received, along with cross-education exercise. SDM is a collaborative approach in clinicians and patients integrate the best available evidence for managing health care problems with patients’ experiences and preferences. It has been recognized for its potential to improve care and outcomes, and has been used to individualize evidence-based recommendations, improve patient adherence and clinical outcomes, increase patient’s knowledge of treatment options, engagement in health care decision making, satisfaction with treatment decisions, and overall care. The reader is referred to Table 2 for more information on shared decision making.

The process of SDM is in three phases: preparing for collaboration, exchanging information about options inclusive of patients’ values and preferences, and affirming and implementing the decision or plan. In this case, preparing for collaboration entailed a discussion about how decisions about his plan needed to be made, what options he had, and allowing the patient to help participate in the plan of care. The method for establishment of load made sense to the patient and considered his level of pre-morbid strength, but also with the understanding that the patient needed to work within limitations for healing and protection of the repair. He needed to understand that although he was frustrated, the protocol that the physician provided was what the physical therapist needed to adhere to, unless told otherwise. Next, the exchange of information involved discussions about blood flow restriction training, something the patient did not know much about but was interested in. Talking about blood flow restriction then led to a discussion about ischemic preconditioning and cross-education, additional treatment methods he was not familiar with but was receptive to the progressive nature of the approach and the evidence associated with it. Treatment options also involved providing a list of potential exercises and activities he could do within restrictions, but also a list of activities and exercises that should not be performed based on recovery timelines. In this phase, patients are equally valued as experts regarding their own values, preferences, and abilities to adhere to options. The subject did his own research not only on EMG activation of the biceps during exercises, but he also researched pull-out strength of various bicep tendon repairs. It was evident that he wanted to respect the repair and healing process but have some evidence to support exercise selection. In the final stage, the physical therapist and the patient agree to the plan set forth as well as compliance with the restrictions suggested. The key of this phase is to both summarize the plan and confirm mutual understanding, ensure congruence with the subject’s priorities and goals, and the subject’s understanding of the condition and its consequences. Obviously the subject’s goal was to be able to train and compete in the future, but he felt five and ten-pound restrictions were not the way to get to the desired outcome based on his pre-morbid status. At the same time, the subject was educated
about potential adverse reactions, including failure of the surgical repair, if he abdicated his responsibility to perform exercises and activities as prescribed within the guidelines provided. Indeed, there were some compliance concerns in the early phases, but once a positive, open relationship was established with clear expectations as well as an appeal for responsible progressions, the subject was more compliant and willing to follow the plan set forth.

The subject had a positive outcome in this case. Not only was range of motion fully restored, but he had symmetrical bicep strength at 60° degrees/second on isokinetic testing, and only an 11% deficit at four months. Given that resisted bicep activities had only been done for eight weeks previously, this case highlights how proper loading may have led to the positive subjective and objective outcomes achieved. The case potentially underscores the potential benefit as well of cross-education, BFR and IPC as adjunctive treatments, but given there was no control, benefits of these modalities is speculative.

CONCLUSION

This case report describing successive loading in a strongman with a distal bicep rupture and subsequent surgical repair highlights the need for clear expectations and communication between providers and patients using a SDM model. The potential to adjust treatment protocols to suit individual patient needs, goals, and preferences (as appropriate within healing constraints) is stressed. Finally, the importance of establishing of possible reference standard to promote loads appropriate for individual patients is highlighted.

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CONFLICTS OF INTEREST

The author offers a continuing education course regarding Blood Flow Restriction Therapy, for which he is compensated. This does not affect the content or presentation of this case report.

Submitted: April 05, 2022 CST, Accepted: September 12, 2022 CST

Table 2. Shared Decision Making Model

<table>
<thead>
<tr>
<th>Stages and Outcomes</th>
<th>Clinician Values, Preparation, and Skills</th>
<th>Patient Values, Experiences, and Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1: Preparing for Collaboration</strong></td>
<td>Comfortable partnering with patients</td>
<td>Communication skills</td>
</tr>
<tr>
<td>• Invite patient to participate</td>
<td>Be empathetic</td>
<td>Health literacy</td>
</tr>
<tr>
<td>• Determine decisions to be made</td>
<td>Actively listen</td>
<td>Past experiences</td>
</tr>
<tr>
<td>• Negotiate priorities</td>
<td>Able to manage time constraints</td>
<td>Cultural norms on health care</td>
</tr>
<tr>
<td><strong>Stage 2: Exchange information on Options</strong></td>
<td>Is knowledgeable of options, benefits, and risks</td>
<td>Identifies and communicates priorities and values</td>
</tr>
<tr>
<td>• Identify patient knowledge, concerns, values</td>
<td>Translates information to patient in nonbiased understandable manner</td>
<td>Ability and willingness to share potential barriers to options</td>
</tr>
<tr>
<td>• Value the expertise of the patient and PT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Outline options with benefits and risks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Deliberation between PT and patient about options</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Clarify and correct perceptions on options</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Determine congruence between patient and priorities and available options</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stage 3: Affirm and implement decision</strong></td>
<td>Active listening and concise summarizing</td>
<td>Ability to summarize back to PT</td>
</tr>
<tr>
<td>• PT summarizes the plan</td>
<td>Negotiation comfort to finalize the plan and accept patient’s preferences</td>
<td>Ability and willingness to accurately report implementation</td>
</tr>
<tr>
<td>• Confirm congruence with patient priorities and goals</td>
<td>Measurement and documentation skills</td>
<td>Identifies outcomes and their measures</td>
</tr>
<tr>
<td>• Patient summarizes the plan and relates concerns and confidence about plan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Document decision-making process and plan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Document implementation and outcomes of plan.</td>
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International Journal of Sports Physical Therapy
Progressive Loading in a Strongman Following Distal Biceps Repair: Re-Thinking Load Progression – A Case Report

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CEUs AVAILABLE FOR ALL COURSES! TO LEARN MORE ABOUT CONTINUING EDUCATION UNITS, VISIT OUR WEBSITE.

WHERE TO FIND US
- STRUCTUREANDFUNCTION.NET
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We are a mission-driven online community seeking to change outcomes with research while helping direct-access clinicians improve the overall awareness and quality of care for concussion patients across the globe with robust educational programming, open office hours, and non-profit partnerships.

**NEW COURSE**

**CONCUSSION**
The Patient Rehabilitation Journey

**DURATION**
Jan-1 thru Mar-26, 2023

**CLASS**
12 Weeks Online

**CONTENT**
On-Demand | Virtual

**CE**
20 or 40 Hours
PT, OT, ATC in All 50 United States

**COURSE FEE**
Starting at $697
Group Pricing Available

A donation will be made to our Non-Profit Partner, Headway Foundation, when you sign up with the IJSPT QR code below.

**REGISTRATION OPEN NOW**
ConcussionCorner.org
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IJSPT
INTERNATIONAL JOURNAL OF SPORTS PHYSICAL THERAPY
IN-OFFICE  TELEHEALTH  RPM

A DIGITAL HEALTH SOLUTION FOR HEP  NOT A REPLACEMENT FOR IN-HOUSE PT, IT'S AN ENHANCEMENT!

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Educating patients and health care professionals about chronic ankle instability and Internal/Brace™ ligament repair

New prospective, randomized trial data confirm that patients with Internal/Brace ligament repair can participate in an accelerated rehabilitation protocol with an average return to pre-injury level of play of 13.3 weeks versus 17.5 weeks with standard repair.¹

<table>
<thead>
<tr>
<th>Return to Pre-injury Level of Play</th>
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</thead>
<tbody>
<tr>
<td>With Internal/Brace (in weeks)</td>
</tr>
<tr>
<td>Standard repair (in weeks)</td>
</tr>
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</table>

Postoperative management is patient-specific and dependent on the treating professional’s assessment. Individual results will vary and not all patients will experience the same postoperative activity level or outcomes.

The Internal/Brace procedure gives patients the flexibility to move freely while protecting the primary repair by limiting abnormal or excessive lateral movement during the healing process.

Reference


Internal/Brace surgical technique is intended only to support the primary repair and is not intended as a replacement for the standard of care using biologic augmentation in a primary repair. Internal/Brace surgical technique is intended only for soft-tissue-to-bone fixation and is not cleared for bone-to-bone fixation.
HydroWorx now has options designed for existing facilities and treatment areas.

RESEARCH SHOWS THAT AQUATIC THERAPY ENHANCES REHAB OUTCOMES.

- Patients and athletes who walk in a HydroWorx pool are better equipped to transfer what they learn to land than their counterparts who engage in self-directed shallow water walking.
- Aquatic therapy is beneficial to achieve threshold-intensity training while lowering the stress on the joints that is caused by land running.
- The benefits of water therapy on the underwater treadmill included reduced soreness, body fat and inflammation while also improving muscle mass and strength performance.
- Clinical results show that athletes who participate in water rehabilitation and land-based post rehabilitation have better scores on postural sway, indicating better balance and fewer episodes of re-injury.
- Benefits of hydrotherapy exercises included a lean body mass increase with underwater treadmill training, with gain seen mainly in the legs.