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ABSTRACT

The ability to decelerate is a key component of any successful rehabilitation program, yet it is often overlooked in favor of more traditional forms of rehabilitation and training. Deceleration, which is defined as the ability to reduce speed or momentum and stop or change direction, can be a key component of successful rehabilitation. The deceleration index is a new metric being used by some physical therapists and rehabilitation specialists to improve patient outcomes. The index is based on the principle that deceleration forces should match those created with acceleration. When patients can quickly and efficiently decelerate during physical activity, they are less likely to experience pain or injury. While the deceleration index is still in its early stages of development, there is promising evidence that it could be the missing link in effective rehabilitation. In this editorial commentary, we’ll explore what the deceleration index is and why it is important to the rehabilitation process.

Key Words: Rehabilitation, momentum, deceleration, deceleration index, acceleration.

Rehabilitation providers know that the ability to change direction quickly is essential for the success of any athlete. Performance relies heavily on athletes’ ability to react quickly in sports-specific situations, especially with regards to agility, coordination, and change of direction (COD). Higher intensity accelerations and decelerations are fundamental components of COD movements and are integral to successful performance of COD. To date, change of direction speed (COD-S) tests are commonly used to identify an athlete’s performance capability and potential risk of injury. To fully assess an athlete’s ability to quickly change direction, a measurable evaluation tool should be used. Unfortunately, change of direction has been measured as a time-to-completion to perform the task. When using the total time for a change of direction test, one assumes that the COD is simply one measure of the athlete’s ability. While this measure can grossly compare left and right COD ability and asymmetry, it gives very little insight into the component parts of COD. COD incorporates key qualities associated with athletic performance such as acceleration, deceleration, and directional changes. In addition to these key qualities, the demands of deceleration are increased in athletes that have a greater body mass. Nimphius et al proposed that the change of direction deficit (COD-D) may better distinguish an athlete’s COD ability compared to a simple time-to-completion in a COD-S test. Specifically, the COD-D is calculated as the difference between COD-S test time and the time taken to cover the same total distance in a linear sprint. Some investigations have reported that athletes with faster sprint times displayed a larger COD-D, while others have found the contrary. It is possible that sprint momentum, which is a function of velocity and body mass, may be more closely linked to COD-D because momentum better represents the mechanical
demands associated with the COD than velocity alone.11

While most research and training have been directed at increasing an athlete's power or ability to accelerate, the ability to decelerate may be more important and the missing link in rehabilitation. Deceleration refers to the ability to slow down quickly and efficiently from one activity or movement to another, thereby allowing the individual to adjust their momentum and reduce the risk of injury. The ability to decelerate is a key component of any successful rehabilitation program, yet it is often overlooked in favor of more traditional forms of increasing power and speed. In this paper, we will examine the role deceleration plays in rehabilitation and how the change of direction deficit can impact patient outcomes.

**What is Deceleration and Why is it Important for Rehabilitation**

Deceleration can be defined as the ability to reduce speed or momentum with respect to time. Harper12 has defined deceleration as a player's ability to proficiently reduce whole body momentum, within constraints, and in accordance with the specific objectives of the task (i.e., braking force control), while skillfully attenuating and distributing the forces associated with braking (i.e., braking force attenuation). Deceleration is vital in change of direction, and a deficit in this category can have a major impact on the patient's performance. Therefore, deceleration is a fundamental skill that must be developed in order for an athlete's to successfully complete their rehabilitation program. In addition to having an impact on the athlete's performance, a decrease in the ability to quickly decelerate or quickly reduce momentum could lead to injury.11 Poor deceleration capability has been identified as a potential mechanism associated with non-contact ACL injury due to the high forces generated during the deceleration.13,14 Additionally, due to the high eccentric braking demands associated with deceleration, this may have the potential to induce muscle damage.14 High deceleration forces may be linked to eccentric induced muscle damage. Researchers have reported elevated levels of indirect muscle damage biomarkers such as creatine kinase (CK) during the 72 hour period following repeated sprints with intense decelerations.16,17

Similar findings have been reported between the number of high-intensity deceleration actions and CK levels post-competitive match play in team sports, such as soccer.18,19 In these instances, the eccentric braking force requirements of deceleration can impart damage on soft-tissue structures through high muscular tensions that can disrupt the structural integrity of the muscle fibers and result in myofibrillar degeneration, which may leak CK into the blood plasma.15,20 If the muscular system has a decreased capacity to attenuate high eccentric loading forces, it may lead to loading beyond the tissues structural capability, causing muscle strain or tearing.

**Introducing the Deceleration Index - What is it and why is it important for athletes.**

Measuring an athlete's ability to decelerate and accelerate quickly is essential for assessing their performance. Using motion capture devices, force plates, and wearable technology, a clinician can observe changes in speed throughout the movement. The deceleration index is a measure of the rate at which an object slows down relative to its ability to accelerate. This measure has typically been used to describe the braking performance of a vehicle. In the automotive industry, the deceleration index is usually expressed in terms of gravitational-force, where 1 g is the acceleration due to gravity. For example, if a car has a deceleration index of 0.5 g, it means that it can slow down at a rate of 0.5 times the acceleration due to gravity. The higher the deceleration index, the faster the vehicle can stop. The deceleration index can be used to compare the braking performance of different vehicles and to determine whether a vehicle’s brakes are operating properly.

In both performance and rehabilitation, it is important to focus on both acceleration and deceleration to ensure that the body is able to move efficiently and safely. Acceleration time is the time it takes for the same athlete to reach their maximum speed from a standing start or a slower pace. In this case, both acceleration and deceleration are determined using speed difference and time. The basic formula for calculating acceleration is the change in velocity (Δv) over the change in
time ($\Delta t$), represented by the equation $a = \Delta v / \Delta t$. This allows you to measure how fast velocity changes in meters per second squared (m/s$^2$). Deceleration can be described as the opposite of acceleration and is the time it takes for an athlete to come to a complete stop after sprinting or performing another high-speed activity. Deceleration can be calculated by dividing the final velocity minus the initial velocity, by the amount of time taken for this drop in velocity. Much like acceleration, deceleration plays a key role in an athlete's change of direction speed. Athletes can increase their COD-S by improving deceleration techniques and learning how to properly use deceleration throughout their movement. Ideally, an individual should be able to create a deceleration force equal to or better than the acceleration force.

By dividing the deceleration time by the acceleration time, the deceleration index provides a measure of how quickly athletes can slow down relative to how quickly they can speed up. The deceleration index refers to the ratio of deceleration (or braking) force to acceleration force in the body's movement patterns. This measurement is important in rehabilitation because it can indicate how well an individual is able to control their movements and prevent injury. A high deceleration index suggests that an individual is able to effectively control their movements and reduce the risk of injury, while a low deceleration index suggests a lack of control and a potential for increased risk of injury. Therefore, tracking the Deceleration Index can help athletes maximize their performance and safety in competition.

The Deceleration Index (DI) offers a straightforward measure of how an athlete's deceleration compares to their acceleration. The deceleration index can be useful in a number of contexts. For example, in team sports, such as basketball or soccer, the ability to quickly decelerate and change direction is often critical for success. A high deceleration index indicates that an athlete is able to slow down quickly and efficiently, which may give them an advantage on the court or field. To improve an athletes' change of direction speed or deficit, employing the DI as a measurable metric ensures that their COD-S development is monitored through both acceleration and deceleration phases. This can lead to increased performance, improved safety, and higher quality training for athletes.

The DI can be used to monitor an athlete's progress over time. By tracking changes in an athlete's deceleration index, rehabilitation providers can assess the effectiveness of rehabilitation and training programs, thereby identifying areas for improvement. For example, if an athlete's DI is consistently low, it may indicate that they need to focus more on eccentric training and deceleration drills in their training. Therefore, the DI can be used as a tool to track progress in rehabilitation and identify areas that need improvement.

With rising numbers of sports injuries, there is growing interest in finding solutions through training and rehabilitation. Going beyond just focusing on power and acceleration in training, deceleration training can be a useful tool in the rehabilitation program. COD-S is an integral aspect of an athlete's performance and having an effective measure of deceleration is key to injury prevention and efficient rehab. The Deceleration Index provides a comprehensive understanding of an individual's ability to decelerate versus their acceleration speed. Using this metric, clinicians are able to observe and measure an individual's ability to slow down as well as speed up, thus providing insight into the risk for injury. While research into its efficacy is still ongoing, initial findings suggest that the Deceleration Index has the ability to improve rehabilitation and may reduce the risk for further injury. The use of this metric could have significant implications for those working in the fields of sports medicine and physical therapy. As such, the Deceleration Index is poised to be the missing link in rehabilitation, allowing practitioners to make informed decisions with regards to an individual's training. With further research, athletes may soon reap the benefits of a reliable way to measure progress during rehabilitation exercises and reduce injury risk.
REFERENCES


INTRODUCTION

ALTERNATIVE FLEXIBILITY TRAINING: DO WE NEED ALTERNATIVE METHODS FOR IMPROVING RANGE OF MOTION?

David G Behm,¹ Jose Carlos Aragão-Santos,¹,² Negar Korooshfard,¹,³ Saman Hadjizadeh Anvar.¹

Introduction

Static stretching was a mainstay for decades for warm-ups before activities, training to increase range of motion (ROM), and rehabilitation from injuries.¹ The popularity of static stretching came into question starting in the late 1990s with research reporting acute static stretching-induced performance (i.e., strength, power, balance, sprint speed) decrements.¹,² Recent research has elucidated the weakness of these prior studies, including a lack of ecological validity in terms of static stretching durations, testing times, lack of inclusion of dynamic activities within a warm-up, and nocebo effects among others.¹,² Static stretching produces trivial effects on subsequent performance when less than 60 seconds of stretching per muscle group is incorporated into warm-ups that included dynamic activities.¹,²

Static stretching has recently taken another hit, with commentaries suggesting that stretching need not be incorporated as a fitness component like training for muscle strength and endurance, cardiorespiratory endurance, or body composition since activities such as resistance training, foam rolling, and local vibration can similarly increase flexibility.¹,³ Though static stretching has fallen out of favour as a warmup activity, it still has merit as a means to increase ROM.

While the popularity of static stretching has diminished, the implementation of dynamic stretching during warm-ups has increased.¹,² Our recent meta-analysis reported no significant differences between static stretching, dynamic stretching, and proprioceptive neuromuscular facilitation (PNF) for increasing ROM.³ There were also no significant differences between stretching at higher or lower intensities. Therefore, though dynamic stretching may be an important warm-up component, it does not offer improvements over static stretching for increasing ROM.

Furthermore, the advent of new techniques to increase ROM does not necessarily mean that these alternative methods are better. Therefore, this perspective aims to expound on these alternatives.

Resistance Training Effects on Range of Motion

Although it has been known for centuries that resistance training can improve muscle strength, power, and endurance, our recent meta-analysis documented that resistance training (free weights, machines, Pilates, but not calisthenics) can provide similar ROM increases as static stretching.⁵ Subgroup analyses found that “untrained and sedentary” individuals had significantly higher, large magnitude ROM improvements than the small increases with “trained or active people”. Since resistance training can provide moderate magnitude improvements in ROM, stretching before or after resistance training may not be necessary.

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Foam Rolling Effects on Range of Motion
Foam rolling is a popular modality that acutely and chronically increases ROM without performance deficits. Our recent meta-analysis concluded that foam rolling had a moderate magnitude effect on ROM with >4 weeks of foam rolling training. There were differences between muscles, as foam rolling increased joint ROM when used on the hamstrings and quadriceps, but not ankle dorsiflexion when foam rolling was employed on the triceps surae. We suggested that certain joints with more limited ROM, such as the ankle, or with a prior history of injuries (e.g., sprains) may not be as receptive to foam rolling. Another meta-analysis from our lab revealed no significant ROM differences between single bouts of stretching and foam rolling suggesting they are equally effective. As such, the underlying mechanisms of increased stretch tolerance or soft-tissue compliance would likely be similar for static stretching and foam rolling.

Vibration
Local muscle vibration alone and combined with static stretching have been used to increase ROM. The research findings are diverse, with vibration (35 Hz with 2 mm amplitude) and static stretching augmenting hamstring flexibility more than static stretching alone, while in other studies, local vibration (i.e., 30 Hz at 4 mm displacement, 44 Hz with 0.1 mm displacement) alone induced similar ROM improvements as static stretching, and was more effective than dynamic stretching. The reported mechanisms underlying vibration-induced increases in ROM are increased stretch threshold, augmented blood flow, diminishing muscle viscosity, and decreases in the phasic and static stretch reflexes.

Don't count out static stretching (yet)!
For individuals with injuries that do not permit resistance training, another static stretching benefit is increased muscle strength and hypertrophy with daily static stretching of 10-60 minutes. Prior reviews have reported that static stretching did not have positive effects to prevent all cause injuries. However, our current reviews reported reduced musculotendinous injury incidence, improved balance, and reduced pain with static stretching as part of the warm-up before an activity or as part of a separate training program (≥30 seconds per muscle group with a total duration of ≥5 minutes). Unilateral static stretching can also have global body effects with large magnitude ROM increases in non-stretched limbs.

Summary
Hence, while there are other activities, such as dynamic stretching, PNF, resistance training, foam rolling, and vibration, that can increase ROM, the reported demise of static stretching may be premature, as it provides an array of fitness, performance, and health benefits and can be used in conjunction with other modalities where increased ROM is a priority of the goal activity. While resistance training and foam rolling can contribute to moderate magnitude increases in ROM, individuals who seek greater improvements may wish to augment these activities with stretch training.

References
3. Afonso J, Olivares-Jabalera J, Andrade R. Time to move From mandatory stretching? We need to differentiate "Can I?" from "Do I have to?" Front Physiol. 2021;12:714166.


Scoping Review

Identifying Conservative Interventions for Individuals with Subacromial Pain Syndrome Prior to Undergoing a Subacromial Decompression: A Scoping Review

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Keywords: decompression, shoulder impingement syndrome, shoulder pain, surgical

Background

Subacromial decompression (SAD) surgery remains a common treatment for individuals suffering from subacromial pain syndrome (SAPS), despite numerous studies indicating that SAD provides no benefit over conservative care. Surgical protocols typically recommend surgery only after exhausting conservative measures; however, there is no consensus in the published literature detailing what constitutes conservative care "best practice" before undergoing surgery.

Purpose

To describe conservative interventions received by individuals with SAPS prior to undergoing a SAD.

Study Design

Scoping review.

Methods

An electronic search using MEDLINE, CINAHL, PubMed, and Scopus databases was conducted. Peer-reviewed randomized controlled control trials and cohort studies published between January 2000 and February 2022 that included subjects diagnosed with SAPS who progressed to receive a SAD were eligible. Subjects who received previous or concurrent rotator cuff repair with SAPS were excluded. Conservative interventions and treatment details that subjects received prior to undergoing a SAD were extracted.

Results

Forty-seven studies were included after screening 1,426 studies. Thirty-six studies (76.6%) provided physical therapy (PT) services, and six studies (12.8%) included only a home exercise program. Twelve studies (25.5%) specifically detailed the delivered PT services, and 20 studies (42.6%) stated who provided the PT interventions. Subacromial injections (SI) (55.3%, n=26) and non-steroidal anti-inflammatory drugs (NSAIDs) (31.9%, n=15) were the next most frequently delivered interventions. Thirteen studies (27.7%) included combined PT and SI. The duration of conservative care varied from 1.5 months to 16 months.

Conclusion

Conservative care that individuals with SAPS receive to prevent advancement to SAD appears inadequate based on the literature. Interventions, such as PT, SI, and NSAIDs, are either underreported or not offered to individuals with SAP prior to advancing to surgery. Many questions regarding optimal conservative management for SAPS persists.

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Level of Evidence
n/a

INTRODUCTION

Shoulder pain affects approximately one-third of individuals in a lifetime, and 36-70% of those who experience shoulder pain are diagnosed with either subacromial impingement syndrome or subacromial pain syndrome (SAPS).1-3 Subacromial decompression (SAD) surgery is one of the most common orthopedic procedures utilized to address SAPS with rates increasing 117-254% between 1990 to the early 2000s in the United States.4,5 In the United Kingdom, 21,000 SAPS procedures were performed in 2010 costing nearly £50 million.6 Individuals with shoulder pain who receive a SAD exhibit similar clinical outcomes in pain, function, and quality of life when compared to those who receive conservative management, yet the procedure is frequently performed when individuals fail conservative management.5,6-9

There is no accepted definition for "adequate nonoperative treatment." This requires judgment by the medical team and patient to determine if conservative treatment was sufficient before progressing to surgery.10 Completing conservative care is a common inclusion criterion to receive a SAD in the literature; however, studies seldom describe the provided interventions. This omission does not assist clinicians or patients in determining if adequate care was exhausted, a common clinical challenge, prior to recommending SAD. Standard care for SAPS is outlined in a recent clinical practice guideline (CPG) suggesting the exhaustion of conservative interventions prior to performing a SAD, and recommending that individuals only receive a SAD if functional loss persists following completion of conservative care.5,6 The CPG recommendations include physical therapy (PT), a guided home exercise program (HEP), non-steroidal anti-inflammatory drugs (NSAIDs), education, and subacromial injections (SI).6

PT intervention has high-level supportive evidence to treat individuals suffering from SAPS.11 Several randomized control trials exist highlighting equivalent outcomes and cost savings when individuals receive supervised exercise compared to receiving a SAD.12,13 Additional authors have found enhanced benefits from combined manual therapy (MT) and exercise over exercise alone.14-17 However, to date, PT is not always delivered to individuals with SAPS prior to undergoing a SAD.11,18 Therefore, identifying the PT interventions offered to people with SAPS prior to undergoing a SAD is needed in the attempt to understand why individuals continue on to surgery.19

Based on the current evidence, it is unclear if adequate conservative management is provided to individuals with SAPS prior to considering a SAD. Therefore, the purpose of this review was to describe the conservative interventions received by individuals with SAPS prior to undergoing a SAD in the published research. This information will allow for future critical appraisals (e.g. systematic reviews) in attempt to define adequate management to prevent SAD as well as assist clinicians and patients to determine if adequate care was exhausted before advancing to surgery. A scoping review allows for data extraction without the need for a critical analysis, and it can provide an overview of the available evidence without producing an answer to a discrete research question.20

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses - Extension for Scoping Reviews (PRISMA-ScR) Checklist guided the design for this scoping review.21 The question was registered with the Open Science Framework and OSF Registries (Identification: https://doi.org/10.17605/OSF.IO/EUP9C).

SEARCH STRATEGY

A librarian assisted with the creation of a database specific search strategy for MEDLINE, CINAHL, PubMed, and Scopus. Keywords, boolean operators, MeSH terms, and MeSH subheadings were used. The search was conducted on February 11, 2022. The search strategy for PubMed is as follows and was adjusted to support each database search criteria:

(((((((shoulder[MeSH Terms]) OR ("shoulder impingement syndrome"[MeSH Terms])) OR ("shoulder pain[MeSH Terms]") OR (shoulder[Title/Abstract])) OR (shoulder impingement syndrome)[Title/Abstract]) OR (shoulder impingement syndrome)) OR (subacromial pain syndrome)) OR ("subacromial pain syndrome"[Title/Abstract])) AND (((subacromial decompression) OR ("SAD")) OR ("subacromial decompression")) AND (((orthopedics[MeSH Terms]) OR (surgery[MeSH Subheading]) OR (surgery[Title/Abstract])))

ELIGIBILITY CRITERIA

Peer-reviewed randomized control and cohort studies with subjects diagnosed with SAPS, subacromial impingement syndrome, or subacromial shoulder pain were included since these terms are interchangeable.15,22–24 Both open or arthroscopic SAPS procedures were included.

Studies published between January 2000 and February 2022 were considered since literature from the early to late 2000s began to highlight non-superior results associated with SAPS outcomes.9,15,25 Other inclusion criteria consisted of studies: (1) evaluating conservative interventions for SAPS, subacromial impingement syndrome, or subacromial shoulder pain when compared to SAD, (2) including subjects listed as having completed conservative care but ultimately received a SAD, and (3) subjects who did not receive any conservative care prior to undergoing a SAD. There was no language restriction in order to maximize study inclusion. An attempt to identify a translated study was made if not published in English.

If one or more of the following conditions were present, the study was excluded: (1) subjects had a concurrent

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acromioclavicular or glenohumeral joint separation or dislocation, rotator cuff muscle tear(s), humeral head avascular necrosis, humerus or clavicle fracture, glenohumeral labral tear or insufficiency, calcified tendinopathy, or glenohumeral joint osteoarthritis, (2) subjects had a history of undergoing a prior SAD or rotator cuff repair, a surgical procedure other than a SAD for shoulder pain, a procedure to address either a complete or partial rotator cuff repair concurrently with a SAD, or a total or reverse shoulder replacement, (3) cadaver studies, (4) subjects with SAPS receiving conservative management but unclear if advancement to surgery occurred, (5) follow-up studies performed on the same study population as the initial publication, (6) pharmacological studies focusing on pain management for consecutively scheduled SAD procedure, or (7) the study design was a systematic review, protocol, conference abstract, case study, narrative review, treatment clinical practice guidelines, or was published in a non-peer reviewed journal.

DATA EXTRACTION AND ANALYSIS

Title/abstract and full-text screening was performed independently by two reviewers (JS and GT). Disagreements regarding inclusion were resolved by discussion, and a third reviewer (JY) resolved the discrepancy if no consensus occurred. A quality assessment was not conducted given the purpose of this scoping review.

The same reviewers independently extracted the data meeting the inclusion criteria and collaborated to organize and validate the findings. The data extracted from each included study were: (1) the types and number of conservative interventions (if provided) completed by subjects prior to undergoing a SAD, and (2) duration of care (months) and/or treatment sessions completed, if available. Details for each extracted intervention were collected, such as the number of SI and/or injected medications, NSAIDs dosage and frequency, interventions and exercises used during PT, and exercises prescribed in the HEP as the details were available.

PT specificity was captured since it is a common conservative intervention received by individuals with SAPS.\textsuperscript{12,13,18} PT was defined as an intervention or a group of interventions provided by a physical therapist or physiotherapist. Additionally, only a licensed physical therapist can offer PT services, and the PT provider was identified to ensure a licensed professional rendered PT services. An intervention including no specific provider was categorized as an independent intervention. For example, if PT and ultrasound were separately listed but the provider delivering these interventions remained absent, these were identified as two separate interventions. If there was or was not a specific description of the treatment provided during PT services, it was categorized into specific-PT or non-specific PT, respectively.

For the purposes of this review, a HEP was defined as an unsupervised exercise regimen prescribed by any healthcare provider. The HEP compliance rate, if available, was collected since intervention adherence is associated with improved outcomes.\textsuperscript{26} If a physical therapist delivered the

![Figure 1. Flow diagram for study inclusion](image)

ACJ = acromioclavicular joint; GHJ = glenohumeral joint; AVN = avascular necrosis; OA = osteoarthritis; SAD = subacromial decompression

HEP, it would be categorized as a part of PT. For example, if a study mentioned PT and a HEP separately but did not clearly state the HEP was provided during PT services, then these were classified as two separate interventions. If PT included a HEP, then it was included with PT and considered one intervention.

The data were subsequently reviewed to identify intervention clusters. Intervention clusters were defined post hoc as the most common combinations of interventions (e.g. both PT and SI is one intervention cluster).

RESULTS

The electronic database searches identified 1,426 studies. The scoping review included 47 studies\textsuperscript{7,14,18,27–70} after duplicate removal, title/abstract screen, and full-text review (Figure 1). A hand search produced one additional study.\textsuperscript{38} Two protocol studies\textsuperscript{71,72} were excluded; the two primary results studies\textsuperscript{5,60} based on the initial protocol publications were included. Lastly, Haahr and Anderson\textsuperscript{73} was excluded as this was a follow-up study on the same subject population from Haahr et al.\textsuperscript{42} The reviewer interrater agreement for the title/abstract screen was strong ($\kappa=76$) and moderate for the full-text review ($\kappa=66$). The two reviewers discussed and resolved all discrepancies. See Table 1 for a summary of results.

PHYSICAL THERAPY

Thirty-six studies\textsuperscript{7,14,18,27,30–37,39–42,44,46,47,50,51,54,55,57–60,63–68,72,75–77} (76.6%) included PT/physiotherapy or supervised exercise.
<table>
<thead>
<tr>
<th>Study</th>
<th>Conservative interventions and dosing, if provided*</th>
<th>Number of conservative interventions provided</th>
<th>Physical therapy description and provider*</th>
<th>Amount and duration of conservative treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aydin et al. 201427</td>
<td>• Physiotherapy:</td>
<td>2</td>
<td>Specific, performed by physiotherapist</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>◦ ROM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Isometric strengthening exercises</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ NSAIDs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back et al. 202128</td>
<td>• Conservative treatment</td>
<td>1</td>
<td>None Listed</td>
<td>3 months</td>
</tr>
<tr>
<td>Baltaci et al. 200770</td>
<td>• Physiotherapy</td>
<td>4</td>
<td>Non-specific, performed by unknown provider</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>◦ Stretching</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Strengthening</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>◦ Activity modification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ NSAIDs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Steroidal anti-inflammatory medication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basharat et al. 202129</td>
<td>• Moist heat</td>
<td>3</td>
<td>None Listed</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>◦ NSAIDs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ HEP including isometric contractions for 6-10 seconds, 10-20 repetitions per day for 5-6 days per week up to 12; then for 12-24 weeks progressive resistance exercise 5 times per week</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beard et al. 20187</td>
<td>• Physiotherapy:</td>
<td>2</td>
<td>Non-specific, performed by unknown provider</td>
<td>3 months</td>
</tr>
<tr>
<td></td>
<td>◦ Remedial exercise regimen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ At least one steroid injection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bengtsson et al. 200630</td>
<td>• At least one steroid injection</td>
<td>2</td>
<td>Non-specific, performed by physiotherapist</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>• Physiotherapy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bhattacharyya et al. 201431</td>
<td>• At least one subacromial steroid injection</td>
<td>3</td>
<td>Non-specific, performed by physiotherapist</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>• Local anesthetic injection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biberthaler et al. 201332</td>
<td>• Physiotherapy:</td>
<td>1</td>
<td>Specific, performed by unknown provider</td>
<td>16 sessions for 60 minutes for 3 months</td>
</tr>
<tr>
<td></td>
<td>◦ Heat/cold pack</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>◦ Soft tissue treatment</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>◦ Active training of the periscapular muscles and strengthening of the stabilizing muscles of the shoulder joint</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>◦ HEP (2-3 times per week)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bjornsson Hallgren et al. 201733</td>
<td>• Physiotherapy:</td>
<td>1</td>
<td>Specific, performed by physiotherapist in Physical Therapy Department</td>
<td>3 months</td>
</tr>
<tr>
<td></td>
<td>◦ Eccentric exercise for the rotator cuff</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Eccentric and concentric exercise for scapula-stabilizing musculature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butt et al. 201534</td>
<td>• One or more steroid injections</td>
<td>2</td>
<td>Non-specific, performed by unknown provider</td>
<td>6 months</td>
</tr>
<tr>
<td></td>
<td>• Physiotherapy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cederqvist et al. 202035</td>
<td>• Physical Therapy:</td>
<td>1</td>
<td>Specific, performed by physical therapists</td>
<td>15 sessions within 3 months</td>
</tr>
<tr>
<td></td>
<td>◦ Cold pack 10-15 minutes prior to exercise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Specific exercises following a protocol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Joint mobilization with muscle energy techniques</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Cross friction massage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Christiansen et al. 201638</td>
<td>• Physiotherapy:</td>
<td>1</td>
<td>Specific, performed by physiotherapist</td>
<td>Greater than 5 sessions</td>
</tr>
<tr>
<td></td>
<td>◦ Advice/instruction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>◦ Exercise therapy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Extracted interventions and details per study for scoping review.
<table>
<thead>
<tr>
<th>Study</th>
<th>Intervention Details</th>
<th>Duration</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DeWachter et al. 2005</td>
<td>• Physiotherapy&lt;br&gt;• NSAIDs&lt;br&gt;• Subacromial steroid injections</td>
<td>3 months</td>
<td>6 months</td>
</tr>
<tr>
<td>Diab et al. 2009</td>
<td>• NSAIDs&lt;br&gt;• Physiotherapy&lt;br&gt;• At least one subacromial steroid injection</td>
<td>3-6 months</td>
<td>3-6 months</td>
</tr>
<tr>
<td>Dickens et al. 2005</td>
<td>• Three subacromial steroid injections at six week intervals</td>
<td>1</td>
<td>4.5 months</td>
</tr>
<tr>
<td>Dorum et al. 2017</td>
<td>• Physical Therapy:&lt;br&gt;  ◦ Strengthening and stretching exercises&lt;br&gt;  ◦ Manual therapy&lt;br&gt;  ◦ Oral analgesics&lt;br&gt;  ◦ NSAIDs&lt;br&gt;  ◦ Injections of corticosteroid&lt;br&gt;  ◦ Radial extracorporeal shockwave therapy</td>
<td>5</td>
<td>3 months</td>
</tr>
<tr>
<td>Farfaras et al. 2016</td>
<td>• Physical Therapy:&lt;br&gt;  ◦ Pain-free exercises with gravity forces removed&lt;br&gt;  ◦ Strengthening of rotator cuff and scapula-stabilizing muscles&lt;br&gt;  ◦ Exercises with corresponding leisure activities</td>
<td>1</td>
<td>3-6 months</td>
</tr>
<tr>
<td>Farfaras et al. 2018</td>
<td>• Physical Therapy&lt;br&gt;• NSAIDs&lt;br&gt;• Local steroid injection</td>
<td>3</td>
<td>3-6 months</td>
</tr>
<tr>
<td>Haahr et al. 2005</td>
<td>• Physical Therapy:&lt;br&gt;  ◦ Heat/cold pack&lt;br&gt;  ◦ Soft tissue treatments&lt;br&gt;  ◦ Exercise:&lt;br&gt;  ◦ Active training of the periscapular muscles&lt;br&gt;  ◦ Strengthening of the stabilizing muscles of the shoulder&lt;br&gt;  ◦ Daily HEP</td>
<td>1</td>
<td>3 months including 19 sessions for 60 minutes</td>
</tr>
<tr>
<td>Hawkins et al. 2001</td>
<td>• No prior interventions listed</td>
<td>0</td>
<td>Not Listed</td>
</tr>
<tr>
<td>Holmgren et al. 2012</td>
<td>• Corticosteroid injection&lt;br&gt;• Physical Therapy:&lt;br&gt;  ◦ Eccentric strengthening of rotator cuff (3 sets, 15 reps, 2 times per day)&lt;br&gt;  ◦ Concentric/Eccentric exercises for scapular stabilizers (3 sets, 15 reps, 2 times per day)&lt;br&gt;  ◦ Posterior shoulder stretch (hold 30-60 sec, 3 reps, 2 times per day)&lt;br&gt;  ◦ Shoulder abduction, shoulder retraction, shoulder elevation, neck retraction, stretch of upper trapezius, stretch of pectoralis major&lt;br&gt;  ◦ Manual intervention of posterior GH capsule and pectoralis minor stretching&lt;br&gt;  ◦ Education on posture (thoracic spine extension and scapular retraction)</td>
<td>2</td>
<td>3 months (then HEP for 2 more months)</td>
</tr>
<tr>
<td>Holmgren et al. 2012</td>
<td>• Local anesthetic injection&lt;br&gt;• Physiotherapy</td>
<td>2</td>
<td>3 months</td>
</tr>
<tr>
<td>Study</td>
<td>Interventions</td>
<td>Duration</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>----------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Hultenheim et al. 2011</td>
<td>No prior interventions listed</td>
<td>0</td>
<td>Not Listed</td>
</tr>
<tr>
<td>Husby et al. 2003</td>
<td>NSAIDs, local steroid injections, physical therapy (ultrasound)</td>
<td>3</td>
<td>Non-specific, performed by physical therapist</td>
</tr>
<tr>
<td>Jacobsen et al. 2017</td>
<td>Physical therapy (daily HEP, supervised training of rotator cuff muscles and scapular stabilizers, glucocorticoid injections)</td>
<td>2</td>
<td>Specific, performed by physiotherapist</td>
</tr>
<tr>
<td>Jarvela et al. 2010</td>
<td>Conservative treatment</td>
<td>1</td>
<td>None Listed</td>
</tr>
<tr>
<td>Jenkins et al. 2020</td>
<td>No prior interventions listed</td>
<td>0</td>
<td>Not Listed</td>
</tr>
<tr>
<td>Kappe et al. 2015</td>
<td>Oral analgesics, physical therapy</td>
<td>2</td>
<td>Non-specific, performed by unknown</td>
</tr>
<tr>
<td>Ketola et al. 2009</td>
<td>Rest, NSAIDs, subacromial glucocorticosteroid injections, physical therapy (exercise programs, increase dynamic stability, exercises, massage, heat, TENS, HEP)</td>
<td>4</td>
<td>Specific, performed by physiotherapist</td>
</tr>
<tr>
<td>Khare et al. 2015</td>
<td>Conservative treatment</td>
<td>1</td>
<td>None Listed</td>
</tr>
<tr>
<td>Klintberg et al. 2010</td>
<td>No prior interventions listed</td>
<td>0</td>
<td>Not Listed</td>
</tr>
<tr>
<td>Kohler et al. 2020</td>
<td>Physical therapy: 3 times per week for 2 weeks then 2 times per week for 4 weeks, exercises (shoulder stabilization, lifting against gravity, exercises that focus on extending the spine, exercise therapy using equipment), manual therapy (mobilization of the scapula, cervical and thoracic spine, friction massage, caudal gliding, traction), additional therapies (ultrasound, kinesiotaping, electrotherapy), subacromial injections (bupivacaine with dexamethasone (maximum of 3 with minimum intervals of 2 weeks))</td>
<td>2</td>
<td>Specific, performed by physiotherapist or physician</td>
</tr>
<tr>
<td>Konradsen et al.</td>
<td>Physical therapy</td>
<td>2</td>
<td>Non-specific,</td>
</tr>
</tbody>
</table>

*NSAIDs* = Nonsteroidal anti-inflammatory drugs; *HEP* = home exercise program; *TENS* = transcutaneous electrical nerve stimulation; *Bupivacaine* = local anesthetic; *Kinesiotaping* = tape applied as a therapeutic intervention.
<table>
<thead>
<tr>
<th>Study</th>
<th>Interventions</th>
<th>Duration</th>
<th>Provider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lim et al. 2007</td>
<td>Rest, Physiotherapy, NSAIDs, Steroid injections in subacromial space</td>
<td>2-16 months (mean: 4.6 months)</td>
<td>Unknown provider</td>
</tr>
<tr>
<td>Lunsjo et al. 2011</td>
<td>Subacromial glucocortic steroid injection, Physical Therapy</td>
<td>6 months</td>
<td>Unknown provider</td>
</tr>
</tbody>
</table>
| Magaji et al. 2012            | At least 1 subacromial injection of steroid, Local anesthetic injection, Physiotherapy:  
                                    |          |                   |
|                               | ◦ Global strengthening exercises  
                                    |          |                   |
|                               | ◦ Lifestyle and ADL changes to change posture and strengthen appropriate  
                                    |          |                   |
|                               | ◦ Taping for biofeedback                                                     |          |                   |
| Odenbring et al. 2008         | Physical Therapy, NSAIDs, Subacromial steroid injection                       | 6 months | Unknown provider   |
| Paavola et al. 2018           | Physical Therapy:  
                                    | 15 visits | Specific, performed by physiotherapist |
|                               | ◦ Individually designed progressive HEP                                      |          |                   |
| Paavola et al. 2021           | Physiotherapy, NSAIDs, Corticosteroid injection, Rest                         | 3 months | Non-specific, performed by physiotherapist |
| Rehman et al. 2009            | Conservative treatment                                                       | 6 months | Non-specific, performed by unknown provider |
| Rombach et al. 2019           | Conservative treatment, At least 1 steroid injection                          | Not listed | None listed |
| Rudbeck et al. 2013           | Rest, Exercises, NSAIDs                                                       | Not listed | Non-specific, performed by unknown provider |
| Singh et al. 2014             | Physiotherapy, Subacromial steroid injection, Local anesthetic injection      | 3 months | Non-specific, performed by physiotherapist |
| Nizam Siron et al. 2021       | Physiotherapy, Analgesics                                                    | 1.5 months to 3 months | Non-specific, performed by unknown provider |
| Taverna et al. 2007           | Physical Therapy:  
                                    | 6 months | Non-specific, performed by unknown provider |
|                               | ◦ ROM Strengthening  
                                    |          |                   |
|                               | ◦ Ice  
                                    |          |                   |
|                               | Subacromial corticosteroid injection(s)  
                                    |          |                   |
|                               | NSAIDs  
                                    |          |                   |
|                               | Activity modification  
                                    |          |                   |
|                               | Rest                                                                   |          |                   |
| Wright et al. 2000            | Physical Therapy:  
                                    | 4-6 months | Non-specific, performed by unknown provider |
|                               | ◦ Moist Heat  
                                    |          |                   |
|                               | ◦ Ice  
                                    |          |                   |
|                               | NSAIDs  
                                    |          |                   |
|                               | Steroid injections                                                        |          |                   |
Yeoman et al. 2012

- Physiotherapy
- Two steroid injections

| 2 | Non-specific, performed by unknown provider | 6 months |

*Identified conservative care interventions noted within each study. Dosage, frequency, and other details were listed when available.

- Physical therapy was defined as specific or non-specific. "Specific" included a description of the physical therapy interventions (e.g. manual therapy, home exercise program). "Non-specific" provided no description. The provider for physical therapy services was identified (e.g. physical therapist, physiotherapist, physician, etc.), or labeled as unknown if no provider was stated.

(ADL = activities of daily living. NSAIDs = non-steroidal anti-inflammatory drug. HEP = home exercise program. ROM = range of motion.)

Figure 2. Physical therapy and home exercise use in the included studies.

Twenty-four studies identified non-specific PT and did not provide details for the provided interventions. Twelve studies explicitly described specific-PT interventions. The specific-PT interventions commonly included eccentric or isometric strengthening of the rotator cuff muscles, scapular stabilization activities, modalities, joint mobilizations, pain-free range of motion, or a prescribed HEP. (Figure 2)

Fourteen studies did not identify if a physical therapist provided the interventions (Table 1). Twenty studies specifically mentioned that a physical therapist/physiotherapist provided the PT service. One study provided PT services from either a physical therapist or a physician, and one study rendered services in the Physical Therapy Department. (Figure 3)

Eight studies gave a specific description of the manual therapy method, technique, or target body region.

Seven studies included thermotherapy, and one study provided radial extracorporeal shockwave therapy. Several studies included electrotherapy, ultrasound, and tapping.

MEDICATION AND INJECTIONS

Fifteen studies identified NSAIDs, and two studies provided oral analgesic medications. One study noted "analgesics" while another study noted "steroidal anti-inflammatory medication" without specifying application methods.

Twelve-six studies included subjects receiving at least one SI or more while 16 studies included unspecified amounts of shoulder-related injections. Three studies mentioned receiving glucocorticosteroid injections, while 17 studies noted steroid, and four studies described corticosteroid or cortisone injections. Eleven studies mentioned providing an injection directly into the subacromial space while the remaining studies were non-descript. See Table 1 for a summary of results.

HOME EXERCISE PROGRAM

Six studies included a HEP prescribed by an unknown healthcare provider or a physical therapist. Ultrasound and taping were also reported.
therapist. Five studies \(^{32,42,47,51,60}\) (10.6%) used a prescribed HEP within PT services while one study \(^{29}\) (2.1%) included a HEP without PT. Basharat et al. \(^{29}\) provided a HEP with specific exercise descriptions and dosages; all other studies \(^{32,42,47,51}\) provided no HEP detail. Four studies \(^{29,32,42,47}\) (8.5%) provided performance frequency associated with the prescribed HEP. Frequency was given as daily, \(^{42,47}\) five times per week, \(^{29}\) or a two to three times per week. \(^{32}\) No study mentioned compliance tracking or adherence to the HEP. See Table 1 and Figure 2 for a summary of results.

**DURATION OF CONSERVATIVE TREATMENT**

Three studies \(^{37,40,41}\) (6.4%) provided conservative measures for a range of three to six months. One study \(^{75}\) (2.1%) delivered services for 12-16 months and another 15 studies \(^{27,29-31,34,36,46,48,55,57,59,66-68,70}\) (31.9%) provided interventions for six months. Ten studies \(^{7,28,33,39,42,44,47,52,64,72}\) (21.5%) provided three months of conservative care. One study \(^{56}\) (2.1%) ranged from two to sixteen months, one study \(^{38}\) delivered treatment for 4.5 months, and another provided intervention for 1.5 months. \(^{54}\) Two studies \(^{35,60}\) (4.3%) provided interventions for 15 conservative care sessions, one study \(^{32}\) (2.1%) completed 16 sessions, and one study \(^{18}\) (2.1%) provided more than five visits before undergoing a procedure. Holmgren et al. \(^{14}\) provided conservative measures for three months followed by two months of a HEP. See Table 1 for specific details.

**CONSERVATIVE INTERVENTION CLUSTERS**

Interventions were clustered based on the most common combinations of interventions as reported in the reviewed studies (Figure 4). \(^{7,14,18,27-60,62-70,72}\) Four studies \(^{45,49,53}\) (8.5%) listed no conservative interventions, and four studies \(^{28,48,52,69}\) (8.5%) mentioned "conservative treatment" without description; one study mentioned conservative treatment in addition to receiving at least one steroid injection. \(^{92}\) Thirteen studies \(^{7,14,30,31,34,44,47,54,55,57,58,64,68}\) (27.7%) reported subjects received at least one or more injections combined with PT. Six studies \(^{36,37,41,46,59,67}\) (12.8%) included PT, NSAIDs, and injections. Four studies \(^{51,56,66,72}\) (8.5%) included PT, NSAIDs, injections, and rest or activity modification. One study \(^{38}\) (2.1%) included only injections, and three studies \(^{27,50,65}\) (6.4%) included combined PT and NSAIDs or oral analgesics. One study \(^{70}\) (2.1%) included PT, NSAIDs, and activity modification. Three studies \(^{29,59,65}\) (6.4%) included conservative care interventions unique to that study. Seven studies \(^{18,32,33,35,40,42,60}\) (14.9%) included PT only. (Figure 4)

**DISCUSSION**

This scoping review highlights the variability in the conservative interventions provided to individuals with SAPS before undergoing a SAD, further emphasizing the need for a standard of what is deemed "adequate conservative management." Few studies provided specific intervention descriptions, such as dosage, type, frequency, medication, or duration of care. Additionally, the interventions received by individuals were provided by physical therapists less than half of the time. The findings from this review call attention to the need for specific criteria that should be met in individuals with SAPS, including maximizing the use of conservative management, before advancing to a SAD.

The majority (76.6%) of subjects in this review received some form of PT service. This finding aligns with research indicating PT, including MT and exercise, can positively impact outcomes for individuals suffering from SAPS; however, it questions why individuals continue to undergo surgery. It brings into question whether the PT services rendered are "adequate." The next most commonly delivered interventions included SI (55.3%) and NSAIDs (31.9%). This further brings into question if the standards of care as suggested by Vandvik et al. \(^{6}\) is sufficient to limit progression to SAD. This finding should be taken lightly as many conservative measures may be underreported; therefore, not allowing for a full comparison to recommended standards of care. Lastly, only one quarter of the studies offered specific details related to PT intervention, and less than half indicated that a physical therapist rendered PT services. This lack of transparency does not allow for the determination of whether or not adequate PT was provided.

It is concerning that non-invasive interventions are not consistent or exhausted despite being safe, beneficial, and cost effective since SAD procedures produce similar outcomes to conservative care. \(^{3,6-9}\) Furthermore, no conservative interventions were reported in 8.2% (n=4) of the included studies. \(^{4,45,49,53}\) This finding supports the inadequate attempts to offer effective conservative intervention prior to undergoing a SAD, and aligns with prior research on rotator cuff related pain conducted by Naunton et al. \(^{12}\) However, caution in making this conclusion is important as operative studies are not typically focused on detailing conservative measures prescribed prior to undergoing a SAD.

Vandvik et al. \(^{6}\) recommended that individuals with SAPS receive a guided PT program, including a supervised exercise program and patient education, before undergoing surgery. A majority of the included studies offered PT services to subjects prior to receiving a SAD, which aligns with conservative treatment recommendations \(^{3,6,12}\); however, over half of the studies lacked an exercise description and purpose for the intervention. Only a quarter of the studies included exercise specifications, such as exercise protocols to the rotator cuff musculature or general information about posture improvements. Additionally, few of the PT interventions included MT while only a third of the studies incorporated modalities. Less than a quarter of the studies included a well-designed HEP despite potential benefits from prescribing a HEP with adequate dosing and frequency. \(^{78}\) No studies measured exercise compliance or compliance to attending PT appointments. \(^{79}\) These findings highlight the literature is not descriptive enough to define if adequate PT intervention was conducted.
Figure 4. Common conservative intervention clusters.

Treatment provided by physical therapists should include specific exercise to the shoulder muscular, thoracic spine, and scapular stabilizers, along with information on psychosocial factors, pain neuroscience education, and behavior change. Future research should provide specific PT intervention details, if rendered PT services prevented SAD, and who provided the PT services since about a third of the studies did not list the provider of PT services. Providing specific intervention details allow for a better understanding of the completed services. Omitting intervention descriptions consequently limits outcome reproducibility in future research or in a clinical environment. Clinicians do not know the specific intervention type or dosage to use to enhance patient outcomes. Therefore, it is recommended to use a set structure to improve the recreation of a study’s result. The Template for Intervention Description and Replication (TIDieR) or Consensus on Exercise Reporting Template (CERT) can guide exercise intervention description; the modified CERT could guide MT intervention and dosage. Enhanced intervention description, including exercise and MT, will allow for treatment efficacy to be measured and act as a valid comparator to surgery.

SI served as the second most provided conservative intervention. Despite the high prevalence for this intervention in the reviewed literature, few studies mentioned the site of the injection, medication, or dosage. Approximately one-third of the included studies in this scoping review did not provide the injected medication or specify the number of injections, which aligns with prior research findings. Sun et al. observed irregularities in treatment protocols including the maximum number of injections to administer to a patient with SAPS prior to determining if they failed treatment. If SI are considered for an intervention to address pain associated with SAPS, the anatomical structure to receive the injection is to the subacromial bursa. The outcomes following SI do not appear to be significantly impacted if performed with ultrasound guidance or with anatomic landmarks when conducted by a trained clinician. A 21 gauge needle can be used to inject a methylprednisolone 40 milligrams and one milliliter one percent lidocaine mix directly into the subacromial bursa but recognize individual medical providers may alter the mixture based on experience and the treatment goal.

Clinical management for SAPS often includes a multimodal approach. Combined PT and SI accounted for the most common (27.7%) conservative intervention grouping prior to undergoing surgery. These interventions were typically provided over a wide range of time (1.5-16 months). Unfortunately, an effective duration of conservative care prior to considering advancement to surgery remains unclear. Additionally, the timing of when conservative care is delivered remains unknown. For example, it is unknown if receiving PT and SI concurrently leads to an optimal outcome, or if sequential intervention prescription may work best (e.g. PT followed by SI, or vice versa). Several unknowns remain to best define adequate conservative management for SAPS to limit advancement to surgery.

LIMITATIONS

Only studies in the English language were included in the review despite attempts to identify translated studies. Also, no quality assessment was performed, which may limit the impact of the findings but can guide future systematic reviews. Lastly, there is a lack of high-quality PT CPGs for the treatment of nontraumatic shoulder pain. This makes...
determining exercise type, dose, duration, timing, and expected outcomes recommendations difficult.\textsuperscript{13,89}

CONCLUSION

Conservative management for SAPS offers an equally advantageous outcome when compared to SAD. Many individuals continue to receive a SAD despite conservative care, bringing into question what is "adequate care" for individuals with shoulder pain. The findings from this scoping review indicate that typical interventions to conservatively manage pain, such as PT, NSAIDs and SI, are underreported or not offered to individuals with SAPS prior to undergoing a SAD. PT intervention shown to positively impact outcomes was underutilized in many studies, further highlighting that adequate care may not be utilized. The inadequate level of conservative care offered does not allow for a valid comparison to surgery. There is a significant need to investigate successful conservative interventions to prevent SAD.

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AUTHORS DISCLOSURES

The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the study.

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Systematic Review/Meta-Analysis

The Effect Of Percussive Therapy On Musculoskeletal Performance And Experiences Of Pain: A Systematic Literature Review

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Keywords: physiological adaptations, physical therapy, muscle strength, flexibility, pain

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Background
There is a lack of specific research on the effect of percussive therapy (PT) delivered by massage guns on physiological adaptations. This systematic literature review investigates research conducted on the effects of PT interventions on performance in strength and conditioning settings, and on experiences of musculoskeletal pain.

Purpose
To determine the effect of PT delivered by massage guns on physiological adaptations: muscle strength, explosive muscle strength and flexibility, and experiences of musculoskeletal pain.

Study Design
Systematic literature review.

Methods
Data sources (CINAHL, Cochrane Library, PsychInfo, PubMed, SportDISCUS and OpenGrey) were searched from January 2006 onwards for full text literature in any language involving adult populations receiving PT delivered by massage guns, directly to any muscle belly or tendon, with comparisons to an alternative treatment, placebo or no treatment. Literature with outcomes relating to acute or chronic physiological adaptations in muscle strength, explosive muscle strength, flexibility or experiences of musculoskeletal pain were included. Articles were assessed for quality using the Critical Appraisal Skills Programme and PEDro scores.

Results
Thirteen studies met the inclusion criteria. All studies had limitations in methodological quality or reporting of findings but still included contextually-rich details that contributed to the overall narrative synthesis. A significant relationship was found between a single application of PT delivered by massage guns and an acute increase in muscle strength, explosive muscle strength and flexibility, with multiple treatments eliciting a reduction in experiences of musculoskeletal pain.

Conclusion
PT delivered by massage guns can help improve acute muscle strength, explosive muscle strength and flexibility, and reduce experiences of musculoskeletal pain. These devices may provide a portable and cost-effective alternative to other forms of vibration and interventions.

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INTRODUCTION
RATIONALE

Percussive therapy (PT) was developed in the 1950’s by Robert Fulford through the introduction of the percussion vibrator which was applied to local areas of the body for deep tissue osteopathic treatment for musculoskeletal pain.1 The first commercial massage gun was invented in 2008 and in recent years, there has been an increase in popularity of handheld devices for personal and professional therapeutic use, as well as by strength and conditioning coaches and athletes to elicit potential performance gains.2 The use of massage gun technology, often referred to as PT, involves “floating” the device over the surface of the skin, applying vibration and rapid pulses in short bursts of pressure to the muscle belly or tendon.3,4 The application is comprised of a triad of characteristics; frequency (Hz), amplitude (mm) and torque (lbs),5 and mimics the therapeutic effects of tapotement massage therapy, where rhythmic percussive strokes are applied to the body with a cupped hand.6

The impact of vibration on physical performance parameters and experiences of pain has been extensively researched, using an array of devices. Vibration is delivered by mechanical vibration, where the energy is transferred from the device directly to the tendon or muscle6 or indirectly through the feet while standing on a platform or the hands by holding a device.7 These forms of delivery can include cycloidal vibration,8 oscillation vibration,9 local vibration therapy,10 whole body vibration therapy (WBV)11 and handheld vibrating equipment.12 Reviews to date have adopted an umbrella term of "vibration therapy" to encompass a range of devices and treatments.13 Vibration therapy has been found effective in promoting acute adaptations in pain reduction,14 increasing strength15 and improving flexibility16 after single and multiple treatments.

Despite this extensive literature there is a lack of specific research on PT delivered by massage guns and the effect on physiological adaptations. A systematic literature review was deemed appropriate to investigate research conducted on PT and the effects of PT interventions on performance in strength and conditioning settings and on experiences of musculoskeletal pain. Identifying the most effective PT protocols would allow researchers to develop targeted interventions to support physiological adaptations and reduce experiences of musculoskeletal pain.

For the purpose of this review the following definitions were applied:

- **Muscle strength** – ability of a muscle or muscle group to exert force on an external resistance.17
- **Explosive muscle strength** – ability of a muscle or muscle group to rapidly produce speed or large forces.18
- **Flexibility** – ability of muscles and tendons to elongate around a joint.19
- **Musculoskeletal pain** – unpleasant sensory experience associated with the bones, joints or tissues of the body.20

The purpose of this review was to determine the effect of PT delivered by massage guns on physiological adaptations: muscle strength, explosive muscle strength and flexibility, and experiences of musculoskeletal pain.

METHODS

PROTOCOL AND REGISTRATION

The systematic literature review protocol21 was registered with Prospero. Registration number: CRD42021253767.

ELIGIBILITY CRITERIA

Databases were searched from January 2006 to capture any preliminary research prior to the introduction of PT massage guns in 2008, with a final search before completion of the study to include any recent articles. Table 1 details the full eligibility criteria.

The PICO criteria were used to frame the research questions and define the eligibility criteria:

- **Participants** - adult populations aged 18 years and older.
- **Interventions** - PT applied by massage guns directly to the muscle belly or tendon of the intended muscle for treatment in any location on the body.
- **Comparators** – alternative, placebo or no treatment.
- **Outcomes** - physiological adaptations: muscle strength, explosive muscle strength, flexibility or experiences of musculoskeletal pain. Measures of these outcomes included self-reported scores and units of measurement, such as degrees, distance and time.

INFORMATION SOURCES

To provide a comprehensive overview, all existing literature was included, for example primary research studies, systematic reviews and conference papers, providing the full-text version of the articles were available. The search strategy was created in collaboration with all authors (Supplementary file 1). The following electronic databases were searched: PubMed, SportDISCUS, CINAHL, Cochrane Library and Psychinfo. Grey literature was searched for in Google, Google Scholar and OpenGrey using a combination of key words, massage gun, percussion therapy, percussive massage and percussive therapy. In addition, all sources were searched using the following brand names; Addisfit, Exogun, Fluxmassage, Hydragun, Hyperice, Hypervolt, Muscle Gun, Myopro, Physion®, Powerplate®, recyclapro, Therabody, Theragun and Tintam. Finally, reference lists of all relevant studies, reviews and reports were searched.

STUDY SELECTION

Study selection at title, abstract and full text screening was performed by one reviewer and checked for consistency and completeness by all reviewers. Any disagreements were resolved using Table 1 as a basis for discussion. After eliminating any duplicates, an initial screening of titles and abstracts excluded records that did not meet the inclusion
criteria. Each record was classified as ‘include’, ‘exclude’ or ‘maybe’ to identify relevant and exclude irrelevant literature. The researcher was inclusive at this stage and, if uncertain about the relevance of a publication, it remained in. For records that potentially met the inclusion criteria, the full text was obtained and screened. Studies written in a foreign language were professionally translated into English and screened for eligibility. Seven papers required translation from Portuguese, Turkish, Korean, Indonesian, Czech and Spanish. Studies that did not meet the inclusion criteria were listed with the exclusion reason(s) (Supplementary file 2). Two attempts in one month were made to contact original authors to locate publicly unavailable full texts or obtain missing data. Any missing data was not inferred. A flowchart that documents the process outlined above can be found in Supplementary file 3.

DATA EXTRACTION

Data for analysis was extracted from the included studies to assess that all relevant data was captured and that it could be reliably interpreted. Extracted data included participants, study design, interventions, comparators, outcomes, authors, year of study, aim/purpose, type of paper, geographical area, sample size, intervention length, treatment methods, measures of acute or chronic adaptations and key findings that related to the review questions. One reviewer extracted data which was checked for consistency and completeness by all other reviewers, with disagreements resolved by discussion.

CRITICAL APPRAISAL OF INDIVIDUAL SOURCES OF EVIDENCE

The included studies were evaluated using quality appraisal tools. The Mixed Methods Appraisal Tool (MMAT) Version 201822 and Critical Appraisal Skills Programme (CASP) tool25 were tested on two full papers. Both tools have been standardized and validated24,25 and are widely used for systematic review purposes. The CASP tool was selected due to its criteria providing the best cover of the methodologies used in the included studies.

RISK OF BIAS IN INDIVIDUAL STUDIES

One reviewer assessed the risk of bias and methodological quality using the Physiotherapy Evidence Database (PEDro) scale26 which was checked for consistency and completeness by all other reviewers. The PEDro scale awards points ranging from 0-10 and studies were deemed high risk of bias and low quality with a score of <3.27

SYNTHESIS OF RESULTS

Findings from the included studies were synthesised narratively with reference to the narrative synthesis guidance, in order to draw conclusions based on the body of evidence. This guidance focusses on synthesising findings from multiple studies which rely on the use of text to summarise and explain findings, and details specific tools and techniques that can be used in the synthesis,28 the purpose of which is to gain insight into the body of knowledge derived from the review.

RESULTS

STUDY SELECTION

A preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow-chart of the study selection is shown in Figure 1.29

STUDY CHARACTERISTICS

Study characteristics are summarised in Table 2. A total of 255 adult participants were involved in the studies (n = 15), with at least 18.8% of these being female. There were five studies which involved mixed genders, one female case study, four studies focussing only on males and three studies not reporting participant genders.

Eleven studies considered the effect of PT delivered by massage guns on the lower body (n = 7) and the back (n = 4), with the remaining two focussing on the shoulders. Ten studies examined the effect of PT on flexibility, with five of these combining outcomes of pain, muscle strength

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studies were included if they meet all the following criteria</td>
<td>Populations ≤ 18 years</td>
</tr>
<tr>
<td>Investigated percussive therapy delivered by massage guns</td>
<td>Investigated vibration techniques other than percussive therapy delivered by massage guns</td>
</tr>
<tr>
<td>Percussive therapy administered directly to the targeted muscles or tendons for treatment in any location on the body</td>
<td>Percussive therapy administered indirectly and not directly to the targeted muscle or tendon for treatment in any location on the body</td>
</tr>
<tr>
<td>Literature published in any language. (Articles not in English were translated)</td>
<td>None</td>
</tr>
<tr>
<td>Comparators of alternative, placebo or no treatment</td>
<td>No comparative treatment</td>
</tr>
<tr>
<td>Full-text version of the article was available</td>
<td>Full-text version of the article was not available</td>
</tr>
<tr>
<td>Published from January 2006</td>
<td>Published prior to January 2006</td>
</tr>
<tr>
<td>Study</td>
<td>Geographical location</td>
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<tr>
<td>------------------------</td>
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<tr>
<td>Konrad et al. (2020)²⁰</td>
<td>Austria</td>
</tr>
<tr>
<td>Hernandez (2020)²¹</td>
<td>California, USA</td>
</tr>
<tr>
<td>Park (2020)²²</td>
<td>Unknown</td>
</tr>
<tr>
<td>Study</td>
<td>Geographical location</td>
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<tr>
<td>-------------------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Patel &amp; Patel (2020)³³</td>
<td>Unknown</td>
</tr>
<tr>
<td>Mansuri &amp; Patel (2021)³⁴</td>
<td>Visnagar, India</td>
</tr>
<tr>
<td>Seju &amp; Rajput (2021)³⁵</td>
<td>Visnagar, India</td>
</tr>
<tr>
<td>Study</td>
<td>Geographical location</td>
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<tr>
<td>Jung &amp; Ha (2020)</td>
<td>South Korea</td>
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<tr>
<td>Kayoda (2019)</td>
<td>Unknown</td>
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<tr>
<td>Godemeche (2020)</td>
<td>Porto, Portugal</td>
</tr>
<tr>
<td>Study</td>
<td>Geographical location</td>
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<tr>
<td>-----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Michal (2021)³⁹</td>
<td>Prague, The Czech Republic</td>
</tr>
<tr>
<td>García-Sillero et al. (2021)⁴</td>
<td>Malaga, Spain</td>
</tr>
<tr>
<td>Piñero (2019)⁴⁰</td>
<td>Unknown</td>
</tr>
<tr>
<td>Study</td>
<td>Geographical location</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Kethüdaoğlu &amp; Demirdel E (2021)⁴¹</td>
<td>Turkey</td>
</tr>
</tbody>
</table>

Notes: PT = Percussive therapy, ROM = range of motion, MVC = maximum voluntary contraction, NPRS = numerical pain rating score, VAS = visual analogue scale

Effect sizes interpretation - d = 0.2 small, 0.5 medium, 0.8 large. r = <0.3 small, 0.3-0.5 medium, >0.5 large⁴²
and/or explosive muscle strength. The remaining three papers focussed solely on either explosive muscle strength or pain. Eleven studies included a control group using a range of comparators, such as no treatment, static stretching and foam rolling, and the final two were case studies. Nine of the studies involved one application of PT with treatment ranging from 30 s to 30 min, and four studies administered multiple treatments over a period of one to four weeks. Only one study reported on the effect of PT 24 h and 48 h post treatment, with the remaining studies assessing the acute effects. A variety of outcome measures and application protocols were used across the studies (Table 3), with twelve (92%) studies using a Theragun or Hypervolt massage gun.

CRITICAL APPRAISAL WITHIN SOURCES OF EVIDENCE

CASP tool quality data for the included studies is presented in Supplementary file 4. All studies had limitations in methodological quality or reporting of findings but still included contextually-rich details that contributed to the overall narrative synthesis and the research questions.Caution was therefore taken when drawing on these details. It was deemed in all studies that the benefits of the intervention outweighed any harms and financial costs, and results could be applied to local populations.

RISK OF BIAS

The PEDro scale risk of bias analysis is presented in Supplementary file 5. PEDro scale scores of 0-3 are considered 'poor', 4-5 'fair', 6-8 'good', and 9-10 'excellent'. Total scores of included studies ranged between two and nine, with an average score of 5.92±2.1. It was not possible to distinguish between the methodological quality of the trials and the quality of reporting. No studies reported blinding of participants to the intervention they were receiving, or of the therapists to the intervention they were administering. Although blinding of participants and therapists can minimise bias, it is challenging to achieve as physical therapy cannot be masked in a way as, for example, pharmacological substances can. It is unclear in ten of the included papers if assessors were blinded when analyzing outcomes, risking potential bias to findings.

SYNTHESIS OF RESULTS

This systematic review identified 13 studies addressing the effects of PT delivered by massage guns on the physiological adaptations of muscle strength, explosive muscle strength and flexibility, and on experiences of pain. Results of the individual studies are detailed in Table 2.

EFFECT ON MUSCLE STRENGTH

Two studies considered the effect of PT on muscle strength; lower body and shoulder, representing a minor proportion of the population, with a large variance in age, suggesting results may vary with a broader intervention and limiting a wider application of findings into practice.

LOWER BODY

The application of PT had no influence on planter flexor strength immediately after a single treatment as tested us-
ing a dynamometer, but the effects of multiple treatments or other strength measures were not considered.\textsuperscript{30}

\textbf{UPPER BODY}

The case study focussing on shoulder strength following rotator cuff surgery indicated an increase in muscle strength for the participant who was eight months post-surgery.\textsuperscript{37} While case study designs are important, they limit the application of results to the wider population. However, results from this case study must be viewed with caution due to the limitation of strength being assessed by Manual Muscle Testing (MMT) which lacks inter and intra tester reproducibility owing to the subjective nature of the test.\textsuperscript{48}

\textbf{EFFECT ON EXPLOSIVE MUSCLE STRENGTH}

Four studies considered the effect of PT on lower body explosive muscle strength.\textsuperscript{4,31,39,40} \textbf{OUTCOME MEASURES}

According to studies which measured outcome data with tensiomyography (TMG)\textsuperscript{4,39} and jumping longitudinally\textsuperscript{40} there was evidence of improvements in explosive muscle strength. This is in contrast to Hernandez (2020) where PT, when added to a warm-up, had no impact on explosive muscle strength when assessed by counter-jump testing.\textsuperscript{31} However, this was the only study to report that participants were instructed to wear compressions shorts and no instructions were provided on jumping techniques or squat depth for the counter-jump, which may have impacted the results.

\textbf{COMBINATION OF TREATMENTS}

Piñero (2019) conducted the only study to involve combined treatments.\textsuperscript{30} Myofascial induction (i.e., mechanical stimuli such as pressure or stretching) was paired with PT and administered 15 days after the first treatment of massage and manual vibration. The results did not consider any long-term effect of the first treatment, and it was impossible to establish whether PT alone was responsible for the significant improvement in explosive muscle strength or the proportion attributable to the other treatments.\textsuperscript{40}

\textbf{LONG TERM EFFECT}

In one study the largest increases in muscle contraction were measured in regular users of massage guns suggesting potential benefits of long-term use of PT, however, these results are limited by the omission of statistical data analysis.\textsuperscript{39} García-Sillero et al. (2021) re-examined the effect of PT both 24 h and 48 h after treatment, with the greatest changes reported in time of contraction (Tc) (i.e., the time between 10% and 90% of muscle contraction)\textsuperscript{52} immediately following PT and after 24 h for radial displacement.\textsuperscript{4}

\textbf{GENDER}

Of the few studies including male and female participants, only Michal (2021) reported results separately.\textsuperscript{39} These results showed that PT had a greater effect on explosive muscle strength in women compared to men, with an average increase in the rate of change of contraction as measured by TMG of $4.47\pm11.67\%$ and $3.64\pm4.53\%$ respectively.

\begin{table}[H]
\centering
\caption{Specification of percussive therapy massage guns used in the included studies}
\begin{tabular}{lllll}
\hline
Study & Device & Frequency & Amplitude & Head attachment \\
\hline
Konrad et al. (2020) & Hypervolt & 53Hz & 12mm\textsuperscript{a} & Soft \\
Hernandez (2020) & Theragun & 40Hz\textsuperscript{b} & 16mm\textsuperscript{b} & Standard ball \\
Park (2020) & Yunmai & 30Hz & 10mm & Narrow sided \\
Patel & Patel (2020) & Theragun & 50Hz & Large ball \\
Mansuri & Patel (2021) & Theragun & Unknown\textsuperscript{c} & Unknown\textsuperscript{c} \\
Seju & Rajput (2019) & Theragun & Increasing\textsuperscript{c} & 16mm\textsuperscript{b} & Ball\textsuperscript{d} \\
Jung & Ha (2020) & Hypervolt & 33Hz & 12mm\textsuperscript{e} & Ball \\
Kayoda (2019) & Hypervolt & 53Hz & 10mm\textsuperscript{e} & Ball \\
Godemeche (2020) & Hypervolt & 33/43/53Hz & 12mm\textsuperscript{e} & Ball \\
Michal (2021) & Theragun & 30Hz & 16mm\textsuperscript{b} & Unknown\textsuperscript{c} \\
García-Sillero et al. (2021) & Theragun & 30Hz & 16mm & Standard ball\textsuperscript{d} \\
Piñero (2019) & Hypervolt & Unknown\textsuperscript{c} & Unknown\textsuperscript{c} & Unknown\textsuperscript{c} \\
Kethüdagonlu & Demirdel (2021) & Hypervolt\textsuperscript{d} & 40Hz\textsuperscript{d} & 12mm & Large ball, spinal, bullet\textsuperscript{d} \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a} Author confirmed use of normal device with amplitude verified on Hyperice website\textsuperscript{45} \\
\textsuperscript{b} Amplitude confirmed on Theragun website\textsuperscript{44} \\
\textsuperscript{c} Unable to contact author to verify \\
\textsuperscript{d} Details confirmed directly with author \\
\textsuperscript{e} Details confirmed verified on Hyperice website\textsuperscript{45}
EFFECT ON FLEXIBILITY

Ten studies focussed on the effect of PT on flexibility, including the back,\textsuperscript{35,38,41} lower body,\textsuperscript{3,30,31,35,40} and shoulder.\textsuperscript{36,37} Overall, results indicated an improvement in flexibility in all anatomical locations after PT.

MULTIPLE TREATMENTS

There were three studies which considered multiple treatments of PT.\textsuperscript{33,35,37} Kayoda (2019) highlighted the potential positive effect of long-term use of PT on shoulder flexibility over four weeks, but did not report statistical analysis.\textsuperscript{37} The remaining studies investigated the impact of PT on flexibility of the trapezius after two weeks of treatment\textsuperscript{35} and hamstrings after one week.\textsuperscript{35} All protocols applied a consistent frequency, with the exception of Sejú and Rajput (2021), where the frequency set on the massage gun was gradually increased over the period of the intervention\textsuperscript{35} (Table 2).

SINGLE TREATMENT

There were two other studies which reported on back flexibility; thoracolumbar\textsuperscript{41} and lumbar,\textsuperscript{38} and one focusing on the shoulder,\textsuperscript{36} with all three reporting significant improvements after one application of PT. However, one study used Vaseline when applying PT which may have influenced the positive results observed on thoracolumbar flexibility.\textsuperscript{41} Vaseline is a lubricant which would have enabled the PT gun to glide more easily over the skin but could have impacted body mechanics by applying too much pressure to the targeted muscle.\textsuperscript{49} Further analysis of the study by Godemeche (2020) suggested that PT promoted greater results in lumbar flexibility only in the very active participants, after increasing the intensity on the massage gun over 16 min of treatment.\textsuperscript{38} The effect of PT on the calf muscle was considered by three studies\textsuperscript{3,50,44} with a further study focusing on hamstrings.\textsuperscript{40} Significant acute improvements in flexibility were reported in all studies after one application of PT, despite the variation in measures used to assess outcome data, brand of massage gun, frequency protocol, amplitude and head attachment. Despite these positive findings, there was also evidence to suggest that the alternate method of static stretching was as effective as a single treatment of PT for increasing flexibility.\textsuperscript{3}

EFFECT ON EXPERIENCES OF PAIN

Considerations of the effect of PT on experiences of pain were made by four studies, which involved the back,\textsuperscript{34,35} shoulder\textsuperscript{37} and lower body.\textsuperscript{40} All the included studies used validated measures of pain; numeric pain rating scale (NPRS), visual analogue scale (VAS)\textsuperscript{50} and Oswestry Low Back Pain Disability Questionnaire.\textsuperscript{51}

SINGLE TREATMENT

Piñero (2019) examined the effect of PT on pain experienced hamstrings after one application and reported a reduction in experiences of pain.\textsuperscript{40} However, the study did not report on the cause of pain and results did not consider any long-term effect of the first treatment administered 15 days prior to PT, making it impossible to establish whether PT alone was responsible for the reduction in pain, or the proportion attributable to the other treatments.

MULTIPLE TREATMENTS

Two studies investigated experiences of back pain and involved PT five times per week for three weeks\textsuperscript{34} or three times per week for two weeks\textsuperscript{35} with a gradual increase in frequency set on the massage gun (Table 2). The significant positive results of these studies suggest benefits of long-term PT use, with the potential to explore increasing the intensity of treatment. Mansuri and Patel (2021) also included a further intervention of ergonomic advice, making it difficult to determine the extent of the positive effect of PT alone.\textsuperscript{34} This study focussed on bus drivers so there is no evidence to suggest the results would be transferable to other populations. Kayoda (2019) investigated the effects on shoulder pain by applying PT twice per week for four weeks, reporting an increase in flexibility.\textsuperscript{37} However, the participant also took cannabidiol (CBD) oil for the first week of the trial which may have influenced the results, as CBD oil has been used to manage pain.\textsuperscript{52}

COMPARISON TO ALTERNATIVE, PLACEBO OR NO TREATMENT

Overall, there were greater positive results from PT interventions when compared to placebo protocols, no treatment, or alternative treatments, suggesting a superior effectiveness of PT against treatments such as sports massage, WBV and foam rolling.

NO TREATMENT

Six studies reported statistically significant increases in muscle strength, explosive muscle strength, and flexibility after PT when compared with no treatment.\textsuperscript{4,30,31,34–36} A further two studies did not report statistics, but PT demonstrated an increase in the outcomes of muscle strength, perceptions of pain and flexibility.\textsuperscript{33,37}

ALTERNATIVE TREATMENT

A further five studies compared PT against an alternative treatment (see Table 2) and demonstrated statistically significant increases in explosive muscle strength, flexibility and perceptions of pain after PT,\textsuperscript{4,35,38,40,41} One study reported a statistically significant increase in flexibility from pre to post PT intervention, with the result being comparable with the alternative treatment of static stretching.\textsuperscript{3} Michal (2021) did not report statistical results, but the PT intervention demonstrated a greater increase in pre to post explosive muscle strength compared to the alternative treatment of sports massage.\textsuperscript{39}
PLACEBO

Finally, one study reported no improvement in flexibility after the placebo treatment of ultrasound, compared to a statistically significant improvement after PT.\textsuperscript{38} However, it was not evident if the de-activated ultrasound device touched the skin or hovered over, and whether this may have promoted a physiological response.\textsuperscript{46}

METHODOLOGICAL CHARACTERISTICS

An issue found throughout the literature was the variety of methods used to record the outcome measures. These included dynamometer and manual muscle test for muscle strength, counter jump and TMG for explosive muscle strength, dynamometer and lunge test for flexibility, and NPRS and VAS for experiences of musculoskeletal pain (Table 2). Further heterogeneity was evident in the specification set on the PT massage guns and Table 3 summarises the comparison between protocols used across the 15 included studies. This variety of methods makes it difficult to draw overall conclusions on the studies included and future research should consider developing a standardised protocol.

DISCUSSION

SUMMARY OF EVIDENCE

MUSCLE STRENGTH

Although only represented by limited number of studies, this review found there was a positive effect of PT on upper body muscle strength,\textsuperscript{37} with no changes observed in the lower body.\textsuperscript{30} It should be recognised that this evidence for the positive impact on muscle strength is limited as it is based on a single case-study that utilized a subjective method of strength assessment (MMT), thus questioning the reliability and validity of the results. However, comparisons can be made to a systematic review by Alghadir et al. (2018) which considered the effect of localized vibration on muscle strength. The types of vibration included in the review varied and included, for example, a percussion hammer, electric-powered dumbbell and vibrating cable. While 82% of the included studies found a significant improvement in upper and lower body strength, it was noted there was a lack of robustness and consistency in methodology, thus hindering the recommendation for an effective protocol.\textsuperscript{15} This is consistent with findings in this current review. It should be considered that a review of the application of vibration in sport suggested that a duration of 6 - 30 minutes could lead to a decrease in muscle strength.\textsuperscript{53} Furthermore, a study that considered the effect of vibration on peak torque of the quadriceps 300 days after anterior cruciate ligament (ACL) reconstruction surgery supported the positive results of vibration treatment. There was a statistically significant difference in peak torque between the treated group and the control group, with results indicating an almost complete recovery following vibration treatment.\textsuperscript{54}

EXPLOSIVE MUSCLE STRENGTH

The results of the current review concluded that PT can promote an increase in explosive muscle strength\textsuperscript{4,31,39,40} supporting the narrative review by Germann et al. (2018) on the effect of local vibration on various outcomes, such as muscle strength, power and flexibility.\textsuperscript{15} Overall, the 21 studies reported that local vibration elicits beneficial changes in the outcomes being measured. The term “local vibration” encompassed a wide range of devices such as WBV, vibrating cables and devices strapped over the muscle, resulting in an array of vibration protocols and adding to the uncertainty about the most effective treatment.\textsuperscript{15}

In contrast, the results of this current review on the positive effect of PT on explosive muscle strength contradicts research which investigated the effect of tapotement on ankle flexibility and explosive power.\textsuperscript{55} It is deemed that PT delivered by massage guns mimics the therapeutic effects of tapotement massage therapy\textsuperscript{5} and Mckechnie et al. (2007) reported results which indicated an increase in flexibility, but no change in explosive power.\textsuperscript{55} This is further supported by recent studies investigating the impact of PT on vertical jump height which concluded there was no acute effect on explosive muscle strength after two minutes\textsuperscript{56} or five minutes\textsuperscript{57} of treatment.

FLEXIBILITY

Multiple studies included in this review reported an increase in flexibility after PT,\textsuperscript{5,30,31,33,35–38,40,41} However, there was no significant difference in improvements in flexibility observed after PT, when compared to traditional static stretching.\textsuperscript{3} This indicates that the impact of PT may not be particularly novel in this outcome. There is conflicting evidence of the effect of PT on flexibility of the lower body, with some studies reporting positive effects\textsuperscript{58,59} and other investigations observing no significant adaptation.\textsuperscript{60,61} The positive results are supported the meta-analysis by Osawa and Oguma (2013) which investigated the acute and chronic effects of vibration on flexibility. Conclusions were similar to this current review, in that positive associations were recorded following vibration treatment. The review included 19 articles involving a combination of WBV, cycloid vibration and specifically made equipment. Again, there was diversity in the vibration device settings which prevents identification of the most effective protocol for promoting flexibility adaptations.\textsuperscript{16} A review of the application of vibration in sport suggested a duration of four minutes could elicit increases in flexibility\textsuperscript{53} and the results of the meta-analysis by Osawa and Oguma (2013) are further supported by a recent study which suggested that vibration foam rolling, with the intensity of vibration set at a frequency of 48 Hz, significantly increased flexibility without compromising muscle strength or performance.\textsuperscript{52}

EXPERIENCES OF PAIN

This current review indicates that multiple treatments of PT could reduce experiences of musculoskeletal pain.\textsuperscript{34,35,37,40} This was also evident from a recent meta-
analysis and systematic review which focussed on the benefits of vibration on delayed-onset of muscle soreness (DOMS). Ten studies were included in the review which measured changes using the VAS after a variety of vibration interventions, such as WBV, cycloid vibration and sonic vibration. Results indicated that vibration reduced DOMS at 24 h, 48 h and 72 h, with the suggestion that the greatest effect was evident after 48 h. A number of exercises were used to elicit DOMS, such as downhill walking and strength training which contributed to the heterogeneity between studies, along with the variety in application protocols. This result is further supported by research which concluded that PT was effective in acutely reducing lower body pain resulting from DOMS.

PAIN VS FLEXIBILITY

Studies in this review reported that reductions in experiences of musculoskeletal pain also demonstrated improvements in flexibility. It is worth considering if improvements in flexibility in response to PT play a significant role in pain reduction. Data from previous studies have indicated a relationship between stretching-based programmes and reduced hamstring, low back, quadriceps and anterior knee pain. Interestingly, the Patel and Patel (2020) hamstring flexibility study, also considered changes in experiences of lumbar pain following the same treatment applied to hamstrings. Pain, measured using the NPRS, indicated a reduction in pre (score = 8) to post treatment (score = 2) suggesting that PT had a positive effect on experiences of back pain, and highlighting possible advantages of indirect treatment.

GATE CONTROL THEORY OF PAIN

When PT is applied to the muscle belly or tendon it activates the muscle fibres and induces a tonic vibration reflex, which involves the sustained contraction of the vibrated muscle and relaxation of its antagonist. This stimulation further promotes excitability in the muscle spindles afferent nerve fibres and these impulses are transmitted to the spinal cord and are believed to trigger an analgesic effect, as suggested by the gate control theory of pain. This theory suggests vibration causes a more closed position of the ‘gate’, thereby reducing the sensation of pain.

METABOLIC CHANGES FROM PERCUSSIVE THERAPY

Research suggests that exposure to vibration or PT promotes an increased metabolic activity occurring within the muscles, including increased blood flow, oxygen saturation and temperature. These acute physiological responses may be contributing to the positive muscle strength and explosive muscle strength results seen in this review.

LIMITATIONS

The methodological characteristics of included studies were heterogenous in the variety of methods used to record the outcome measures and the specific vibration parameters. This makes it inappropriate to compare the results of the included studies and draw conclusions concerning the most reliable and effective protocol. As 62.4% of participants across the studies were healthy active young adults, with another 30.2% experiencing pain, the effect of PT on the specified outcomes appears to be most advantageous for these populations and may not be generalisable to other groups. There were a number of studies identified by the search criteria which were published only as conference papers, which did not have full papers available, and these were excluded.

There are also number of strengths we would like to highlight:

- PRISMA guidelines were followed, and stringent inclusion and exclusion criteria were adhered to in the selection of the review articles ensuring transparency and robustness throughout.
- The review used broad inclusion criteria for the paper type (e.g. primary studies, conference presentations, Doctoral theses) resulting in an extensive literature search, enabling literature to be included that would otherwise be missed.
- Some articles were professionally translated from different languages (Portuguese, Turkish, Korean, Indonesian, Czech and Spanish) as it was deemed important to include these studies as they provided information in line with the research questions of this paper.

CONCLUSION

The results of this systematic literature review infer that PT, delivered by massage guns, can promote an acute response in muscle strength, explosive muscle strength, flexibility, and experiences of pain, when compared to alternative, placebo or no treatment. The evidence suggests that PT has an acute effect on improving musculoskeletal performance with a single application, whereas multiple treatments are required to reduce experiences of back and shoulder pain. In addition, there is an under representation of females in sports science and sports therapy research and future studies should look to establish any differences between genders or just the impact of PT on females as a cohort, to achieve an equal knowledge about female participants. Further research should establish a standard, validated treatment protocol to allow analysis across populations and those with specific performance needs or pain, as well as considering the chronic effects of PT and the impact of multiple treatments.
CONFLICTS OF INTEREST

The authors have no conflicts of interest.
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SUPPLEMENTARY MATERIALS

**Supplementary file 1**

**Supplementary file 2**

**Supplementary file 3**

**Supplementary file 4**

**Supplementary file 5**
Systematic Review/Meta-Analysis

Effect of Conservative Interventions for Musculoskeletal Disorders in Preprofessional and Professional Dancers: A Systematic Review

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Keywords: dancer, conservative treatment, prevention

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Background
Preprofessional and professional dancers are among the athletes who sustain the most musculoskeletal disorders. In recent years, conservative treatment and preventive measures have been investigated in this population. However, no systematic review regarding their effectiveness has been conducted.

Hypothesis/Purpose
The aim of this systematic review was to locate, appraise and synthesize the available information on conservative interventions currently used for treating and preventing MSK disorders and their effect on pain and function in preprofessional and professional dancers.

Study design
Systematic review.

Methods
A systematic literature search was conducted using PubMed, CINHAL, ERIC, SportDiscus and Psychology and behavioral science collection. Prospective and retrospective cohort studies, as well as randomized and non-randomized controlled trials investigating conservative interventions for musculoskeletal disorders in preprofessional and professional dancers were included in this study. The main outcome measures included pain intensity, function, and performance. All included studies were evaluated for risk of bias using the Downs and Black checklist.

Results
Eight studies were included in the review. These studies included ballet and contemporary dancers, as well as professional and preprofessional dancers. In total, the studies included 312 dancers, 108 male and 204 female. Studies had a risk of bias that ranged from poor (8/28) to good (21/28) on the Downs and Black checklist. The conservative interventions used included customized toe caps, dry-needling, motor imagery, and strength and conditioning programs. The use of customized toe caps, motor imagery and strength and conditioning programs had promising results regarding pain and function in dancers.

Conclusion
In order to reach a solid conclusion, more quality studies are needed. The addition of control groups to studies, as well as multimodal interventions should be considered.
Level of Evidence

INTRODUCTION

Preprofessional and professional dancers have a 90% lifetime incidence of developing musculoskeletal (MSK) disorders, including injuries and pain.1 Dancers will sustain an average of one to two injuries per season.2–6 Dance-related MSK disorders affect dancers’ physical and mental health, sometimes even threatening their careers.7,8 Hamilton et al. have found that the most injured are the preprofessional dancers who end their career prematurely.5 MSK disorders can also have serious consequences for the school or company where the dancers train.4 A dancer’s absence will affect the training of the other dancers and put financial pressure on their company.7 MSK disorders also carry a heavy personal and societal economic burden, as 60% of injured dancers will require a costly imaging examination or referral for their psychological health.1,3 MSK disorders can occur as a result of trauma or overuse of the MSK system. Overuse injuries account for 66–79% of all MSK disorders.2,3,6,9 Among dancers, overuse injuries are often related to a repeated faulty movement pattern or an excessive mechanical load that increases over time with the progression of their career.9 This highlights the importance of identifying best practices to either prevent or treat MSK disorders.

Even though dance is considered an art form, dancers are often regarded as athletes due to the high physical demand of their practice and therefore benefit from training to prevent injury.10 Many authors have supported the idea that conservative interventions such as strengthening and conditioning programs are one way of improving the dancers’ fitness and decreasing injury risk factors.11–15

Regarding treatment, conservative modalities specific to dancers have emerged in recent years. These types of interventions include physical therapy (e.g., manual therapy, strength and conditioning programs), massage therapy as well as interventions provided by other health care professionals.

However, scientific evidence on the effects and efficacy of conservative interventions to prevent and treat MSK disorders has never been synthesized, and the level of proof for these interventions has not been reported. Considering the high level of injuries among dancers and the unique physical demands of this art form, there is an urgent need for practitioners to identify effective conservative treatments to prevent or treat MSK disorders in dancers.

The aim of this systematic review was to locate, appraise and synthesize the available information on conservative interventions currently used for treating and preventing MSK disorders and their effect on pain and function in preprofessional and professional dancers.

METHODS

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol was registered on the international prospective register of systematic reviews (PROSPERO CRD42021258563).

SEARCH STRATEGY

The following bibliographic databases were searched from inception to August 21st, 2022: Cinahl, Medline, ERIC, Sportdiscus, Psychology and behavioral science collection. A combination of keywords associated to the population (dance, preprofessional, professional) and outcomes (pain, function, performance) were used in the search. The full search strategy is presented in Appendix 1. No language restrictions were applied to the search. Grey literature was searched on the websites of Healthy Dancer Canada and the International Association for Dance Medicine and Science. The reference lists of eligible articles found in the main search were also screened for additional articles.

ELIGIBILITY CRITERIA

The literature review included prospective and retrospective cohort studies as well as randomized controlled trials (RCTs) investigating the effect of at least one conservative intervention on professional and preprofessional dancers. Both injured and uninjured dancers at the time of intervention were included for treatment or prevention of MSK disorders. Case series and case reports were excluded.

Studies involving preprofessional and professional dancers, including ballet, classical, contemporary, hip hop, modern, ballet jazz and/or jazz dancers were included, as long as they represented 75% or more of the sample. Gymnasts, circus artists, tumblers, cheerleaders, and dancers whose main style was not ballet, jazz or contemporary (e.g., folk, irish, spanish, native and traditional dancers) were excluded from this review. These other sports and dance styles were excluded because the physical demands are very different from ballet, jazz or contemporary dance.

Regarding treatments, studies were included if they evaluated non-invasive interventions that aimed to prevent or treat a MSK condition (exercise/stretching, physical therapy, manual therapy, taping, electrotherapy, dry needling, acupuncture, osteopathy, chiropractor, massage therapy, kinesiology, proprioception, motor imagery, and nutrition). Studies investigating surgical procedures, pharmacological treatments, homeopathy or self-treatment were excluded.

Given the limited literature available on the effects of conservative treatment in dancers, no specific comparators were identified. Therefore, studies with conservative treatments versus no treatment, sham treatment or placebo or other types of interventions, including non-conservative treatments were included. Studies including co-interven-
tions were included if they were applied equally to both the intervention and control group.

Two main outcomes were selected in this systematic review: pain and function. Pain outcomes included pain intensity and quality. Included function outcomes were related to range of motion (ROM) or position, flexibility, balance, strength and conditioning (e.g., strength, power, muscular or aerobic performance); movement performance (e.g., task completion, movement quality); motor control (e.g., muscle activation); and time that participants had to refrain from dancing or change their technique.

STUDY SELECTION

The literature search results were uploaded to the Zotero software and duplicates were removed. Teams of two reviewers determined the eligibility of each article by reading the titles and abstracts. Every abstract that appeared to match the eligibility criteria was assessed using the full text. The final selection of articles included in this systematic review was made using the full text. For all three phases, disagreements were resolved by consensus. If a consensus could not be reached, a third reviewer (JBP) was involved.

DATA EXTRACTION

Two teams, composed of two reviewers each, then independently extracted the information for each study included using a standardized data extraction table. The following information was extracted: design of the study, population, sex, sample size, intervention details, outcome measures used, relevant results of the study and risk of bias score. Authors were contacted if necessary.

RISK OF BIAS ASSESSMENT

The articles included were reviewed for risk of bias using the Downs and Black checklist by two independent groups of reviewers.16 This checklist allows the assessment of both RCTs and non-RCTs, and comprises 10 items evaluating reporting of data, three items evaluating external validity, 13 items regarding internal validity and one item evaluating power. Each item is rated 0 (no or unable to determine) or 1 (yes), with the exception of the fifth item on the description of confounders that is rated 2 (yes), 1 (partially) or 0 (no). This tool showed good test-retest and inter-rater reliability with high quality index and internal consistency.16 A total score was calculated by summing all items, and quality was interpreted as excellent (26-28), good (20-25), fair (15-19) or poor (<14).17

STRATEGY FOR DATA SYNTHESIS

Data was aggregated and a narrative critical analysis was conducted. Descriptive data were used to characterize the study population. A narrative report on the findings was completed to provide avenues for future research and practice. A meta-analysis was not attempted.

RESULTS

A total of 2,011 titles were identified following the database search (Figure 1). Once duplicates were removed, 1,112 titles remained. Of those, 1,089 were excluded based on inclusion and exclusion criteria using the titles and abstracts. The full text of 23 articles were obtained and assessed, and 15 were excluded, yielding eight studies that were included in this systematic review.

RISK OF BIAS

According to the risk of bias assessment, two studies were scored as poor,10,18 four were evaluated as fair19–22 and two were rated as good.11,12 Table 1 presents evaluations for each study’s risk of bias using the Downs and Black checklist.

The risk of bias was derived from several factors. Most studies did not clearly describe the distribution of the principal confounders and the adjustments that were made in the analysis to account for those confounders. No studies reported on the possible adverse events of their intervention. Moreover, five out of eight studies failed to describe whether the participants contacted at recruitment were representative of the population and likewise, if the participants included in the study represented the population. Many of the studies had a high risk of bias due to the lack of blinding of the intervention from the participants, health care workers, and staff. Few studies used randomization, which was also one of the main risks of bias. Finally, no studies described how their sample size was sufficient to detect a clinically important change.

STUDY CHARACTERISTICS

Table 2 presents a summary of the characteristics of the included studies. Study designs included two prospective cohort studies, one uncontrolled trial, one within subject quasi-experimental study, one randomized cross-over study, one within-subject experimental study, one pilot RCT and only one RCT.

DANCE SHOES

One crossover study examined two types of toe caps for pointe shoes in professional ballet dancers, who had an onset of hallux valgus or a sprained first metatarsal medial collateral ligament (N=10).19 The effects on pain intensity using the visual analog scale (VAS) and on the hallux deviation angle using X-rays were measured in a single session, where the dancers used two different toe caps. The study found that the customized toe cap caused less pain when dancing en pointe than the standard toe cap. The hallux deviation angle was lower with the customized toe cap compared to the standard toe cap.

DRY NEEDLING

One pilot study explored whether dry needling applied to trigger points on the triceps surae of dancers affects pain,
ankle range of motion and ankle joint torque in plantar flexion at 60, 90 and 120 degrees/second. The researchers randomized dancers to a dry needling intervention (N=5) or a sham dry needling intervention (N=4). Dry needling was applied to trigger points on the triceps surae muscles of professional dancers. Dancers also received two 30-second stretches on a slanted board after the dry needling or sham dry needling intervention. No significant differences in pain (p>0.246) or ROM (p>0.093) were observed within and between groups. There was a decrease in temperature bilaterally, in the triceps surae trigger points, following the sham dry needling treatment (p=0.008) and in the right calf for the dry-needling group (p=0.048). Ankle torque at 60 degrees/second increased for the left calf in the dry needling group from pre- to post-treatment (p=0.027). Ankle torque at 90 and 120 degrees/second showed no significant difference pre- to post-treatment within or between each group (p>0.108).

MOTOR IMAGERY

The non-randomized study by Gildea et al. investigated trunk stiffness and damping of the trunk during a forward or backward perturbation was applied to the trunk. They compared the natural postural response at the pre-treatment condition versus the postural response following a motor imagery intervention that aimed to elicit a fluid response in healthy dancers with (N=22) and without (N=8) a history of low back pain (LBP). The authors found no difference in stiffness between dancers with or without a history of LBP in the natural postural response pre-treatment condition, however there was a significant decrease observed in both groups following motor imagery. They also found that dancers without LBP had significantly higher trunk damping than dancers with a history of LBP (p=0.054) in the natural response condition. However, when using motor imagery to elicit a fluid reaction to the trunk perturbations, dancers with LBP had a similar level of trunk damping to dancers without LBP (p=0.226).

CONDITIONING/TRAINING PROGRAMS

The conditioning and training programs used with dancers were investigated in five studies. The programs used were either the same for all dancers or tailored to an individual's specific needs. Only one RCT was conducted on training programs to prevent injuries in dancers. Roussel et al. found no differences in aerobic capacity and explosive strength after a four-month conditioning program compared to the control group, which followed a health promotion program without any active exercises. It was nonetheless noted that the group that completed the conditioning program showed a decrease in their pain scores on the SF-36 and had fewer lower back pain complaints compared to the control group.

All other studies were prospective and had no control group. Multiple outcomes were investigated, in-
Table 1. Risk of bias

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External validity

| Selection of participants     | +                | -                 | -                    | -                | +                    | +                | -                | -                |
| Subjects are representative of the population | +  | -                | -                    | -                | +                    | +                | -                | -                |
| Staff, places and facilities representative | +  | +                | +                    | +                | +                    | +                | -                | -                |

Internal validity – bias

| Attempt to blind the interventions | -    | -                | -                    | -                | -                    | -                | +                | -                |
| Attempt to blind the evaluator   | -    | -                | +                    | -                | -                    | +                | -                | -                |
| Data dredging                   | +    | +                | +                    | +                | +                    | +                | +                | -                |
| Adjusted for different lengths of follow-up | +  | +                | +                    | +                | +                    | +                | +                | -                |
| Statistical tests appropriate   | +    | +                | +                    | +                | +                    | +                | +                | -                |
| Compliance with intervention reliable | -  | +                | -                    | -                | +                    | -                | +                | -                |
| Main outcome measures valid and reliable | +  | +                | +                    | +                | +                    | +                | +                | -                |

Internal validity – confounding

| Patients in groups from the same population | +    | +                | +                    | +                | +                    | +                | -                | +                |
| Patients in groups from the same time period | -    | +                | -                    | +                | -                    | -                | -                | -                |
including aerobic endurance, strength, function, balance, stability and injury incidence.

Aerobic endurance was investigated using the Aerobic Power Index submaximal test in a study by Mistiaen et al. (N=40). They administered a weekly training program for six months that included aerobic endurance, local muscle strengthening and endurance, motor control, proprioception and coordination. A significant increase in aerobic capacity was found in the dancers who completed the training program. However, a similar program was used in the above-mentioned RCT by Roussel et al., and no differences were found between the experimental and control groups.

Strength was measured using the standing broad jump test and a subjective assessment of dancers. Following their training program, Mistiaen et al. found that the explosive strength of the dancers increased from pre- to post-treatment. However, no differences between the intervention and control groups were found when introducing a control group, as was done in the study by Roussel et al. Based on subjective data, Welsh et al. (N=8) found that dancers, who initially mentioned that their dancing was negatively affected by poor back strength, did not feel this way anymore following the strength training program.

Function was evaluated using the Dance Functional Outcome Survey and arabesque height was measured using the angle on a printed photograph. Long et al. administered a bi-weekly training program for a five-week period to professional contemporary ballet dancers (N=6). This training program included basic movement pattern exercises (bridges, planks, single leg deadlifts, lunges, squats, step ups and jumping). The movements became more specific to dance as the program progressed. They found that dancers had higher function following the program, as measured by the Dance Functional Outcome Survey. Welsh et al. compared mean arabesque height in dancers following a back strengthening program from pre- to post-treatment. They found an increase in arabesque height on photographs, although this difference was not supported by inferential statistical analysis.

Balance was evaluated using the modified Star Excursion Balance Test in one within subject quasi-experimental study. Following the training program, balance increased in dancers from pre- to post-treatment. However, a within-group difference was found from the pre- to four-month follow-up for only one composite score of balance.

Stability was evaluated only in one within subject quasi-experimental study, using the single-leg hop for distance for ankle and knee stability, as well as the Closed Kinetic Chain Upper Extremity Stability Test for upper extremity stability. Following the training program, the ankle and knee stability of the dancers increased from pre- to post-treatment, as well as from pre- to four-month follow-up. Similar results were obtained for upper extremity stability, although there was no within-group difference from pre- to four-month follow-up.

Injury incidence was evaluated using the time-loss definition and assessed by an in-house physiotherapist. In a prospective cohort study, Allen et al. followed professional ballet dancers for three years (Year 1 N=52, Year 2 N=58, Year 3 N=53). The program for the first year was based solely on results from a pre-season screening using the Functional Movement Screen (FMS™). The program for years two and three was based on both the FMS™ results and the dancer’s injuries, cause of injuries, and the final outcome of the previous injuries (stil injured, recovered with compensations, or recovered). It was found that the injury rate dropped in the second and third year compared to the first year. The RCT by Roussel et al. also found a decrease in reported injuries following a conditioning program, although this was specific to low back injuries.
DISCUSSION

The aim of this systematic review was to describe the different conservative interventions commonly used and their effect on MSK disorders in preprofessional and professional dancers. MSK disorders are a major concern for dancers, and this review identifies different conservative treatments that have been used, as well as the level of evidence supporting each intervention. The most commonly reported treatment was the training or conditioning program, whether it be general or individualized. The use of dry-needling, customized toe caps and motor imagery was also described in literature. The interpretation of these findings is however limited by the low number of studies as well as weak methodological designs and moderate to high risk of bias for the majority of the included studies.

The use of appropriate footwear is crucial for dancers. For example, the use of “dead” pointe shoes, i.e., pointe shoes that have lost structural integrity in the toe box or shank, was reported to affect muscle activation and biomechanics, which makes it more demanding for dancers to execute common movements, such as relevé or arabesque.24 In a randomized crossover study with a moderate risk of bias, the use of customized toe caps seemed to yield positive results for pain and the deviation angle of dancers with hallux valgus or first metatarsal hypermobility. However, costly customized toe caps are not commonly available to most dancers, and few dancers would have access to this kind of comprehensive assessment. Therefore, while interesting, this treatment would be difficult to implement in current clinical practice. Moreover, since the study included only a single session with pre- and post-treatment evaluations, long-term use should also be investigated. An analysis of costs and benefits could be conducted to evaluate the relevance of implementing this intervention in dance schools and companies.

The investigation of novel treatment strategies, such as dry-needling, customized toe caps and motor imagery, while interesting, showed a high risk of bias that impeded strong conclusions. Dry needling is a treatment technique that is usually delivered by a physical therapist, which has yielded promising results for decreasing pain, increasing range of motion and improving functional outcomes as well as strength in athletes.25–27 Indeed, in overhead throwing athletes with scapular dyskinesia, a RCT showed that the combination of dry-needling and manual therapy was more effective than manual therapy alone to reduce pain while playing and increase function during sport.25 Similarly, dry needling of trigger points in the gluteus medius and quadratus lumborum combined to exercise therapy was more effective than exercise therapy alone to reduce pain and increase function in female athletes with patellofemoral pain.26 Another RCT found that, in elite soccer players, dry needling was more beneficial for hip flexors endurance and hip range of motion in the hip, after the treatment but also 4-weeks post-treatment compared to placebo laser.27 In the current systematic review, although there was a decrease in temperature, as measured by a thermometer, of the trigger points and an increase in plantar flexor torque at 60 degrees/second from pre- to post-treatment, the results from the pilot RCT by Janowski et al. had a high risk of bias. Some dancers were familiar with the twitch response that can be elicited through dry needling, and they could have thus guessed their allocation group. There were also two dancers who were not blinded in the sham group because they requested not to receive the dry needling intervention. Moreover, the sample was small and probably could not detect significant change. Considering the literature on dry needling and its positive effect on other athletes, this intervention should be further investigated in dancers.

While research on motor imagery in dancers is still emerging, the effect of this technique on performance is supported in different populations of athletes.28–30 In athletes, it has been mostly studied in terms of its effect on performance rather than prevention or treatment of injuries. In basketball players, it was found that motor imagery protocol was more effective to improve physical performance compared to a control and preintervention group.28 Its use has also been supported in non-athletes in the rehabilitation of knee injuries by a recent scoping review.31 Indeed, motor imagery interventions contributed to a better clinical outcome of function and pain.31 In dancers, motor imagery practice seems to improve performance of movements,32 and even mood.33 Moreover, dance teachers have been using images to convey the proper way of completing movements for decades.32 The study by Gildea et al. is of particular interest as it shows that dancers with a history of LBP and impairments in trunk stabilizer activation22,34 can use motor imagery to increase their damping abilities to the same level as dancers without a history of LBP. Motor imagery practice is especially interesting since it requires no costly equipment and could be implemented by either health care professionals or dance teachers. However, this study had a moderate risk of bias. Future studies should investigate the use of motor imagery in combination with other interventions to prevent or treat dancers with MSK conditions. The majority of studies included in this review investigated conditioning or training programs. These interventions have been widely researched in other athletes and have proven to be effective to prevent certain injuries, especially among female athletes.35–37 Indeed, a systematic review found that neuromuscular training, including interventions such as strength, balance and proprioceptive exercises, was effective to prevent ankle injuries in female athletes.35 In another systematic review, it was found that strength, balance and plyometric exercises were effective to prevent anterior cruciate ligament injuries in male and female athletes.36 An additional systematic review on female athletes found that neuromuscular training including plyometric exercises was the most beneficial to prevent anterior cruciate ligament injuries.37 While these findings are important and relevant, dancers are a unique population as they are both artists and athletes. The studies included in this review combined multiple components in their programs. They were delivered between one and three times per week, for a period ranging from five weeks to three years.10–12,18,21 Uncontrolled prospective studies with
FUTURE DIRECTIONS

In a sport with such specific demands and high expectations of performance, effective treatment that allows the artist to return to dancing is imperative. In the literature on the treatment and prevention of MSK disorders in athletes, multimodal interventions seem to be key in improvements of pain, function, and a prompt return to sport.

Future research on the treatment of MSK disorders in dancers should therefore include multimodal approaches, including training and conditioning programs integrated to novel components like motor imagery and dry-needling. Moreover, future research should focus on conservative interventions adapted to the athlete and type of dance, as well as to the athlete’s development during the rehabilitation or prevention program. More importantly, studies need to use a robust design and include control groups to ensure that the sole taking care of dancers or placebo effect does not interfere. In order to analyze the changes in the incidence of MSK disorders and injuries following conservative treatments, there is an urgent need to establish a clear and standardized definition for MSK disorders in dancers.

LIMITATIONS

This systematic review is inherently limited by the quantity and quality of the studies included. Since there were no exclusion criteria based on the risk of bias assessment, all studies were retained for the review regardless of their quality. Interpretation of results are limited as most studies did not include a control group or blind the dancers to their group allocation. Moreover, most studies also had a small sample size and no sample size calculation to justify such a limited number of participants.

The few studies included in this review had widely different populations in terms of professional or preprofessional status and dance style. Robust conclusions that would apply to the entire population of dancers that were studied is therefore difficult considering the different training, schedule, and mindset of these dancers.

CONCLUSION

Although this review highlights some promising treatment and prevention avenues for dancers, a strong interpretation of results was limited by the insufficient acknowledgement of confounders, concerns regarding external validity, insufficient power, as well as lack of randomization and blinding participants, health workers and staff. More high-quality studies are needed to reach any solid conclusions. Dance researchers should focus on the addition of control groups to their studies, as well as multimodal interventions. Indeed, the use of multimodal conditioning programs yielded significant early results on pain, function, and balance in uncontrolled prospective studies. This multimodal treatment should be investigated in RCTs. Moreover, researchers should explore the idea of individualized conditioning programs, tailored to the dancers’ limitations.

ACKNOWLEDGEMENTS

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CONFLICTS OF INTEREST

The authors report no conflict of interest.

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Original Research

Spatiotemporal Parameters of Gait Among Adolescent Athletes with Concussion When Performing a Visuospatial Cognitive Task

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Keywords: adolescent, concussion, dual-task, gait

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Background
Adolescent athletes aged 10 to 19 years are at the highest risk of experiencing sport-related concussions (SRCs). Despite the known deficits and battery of assessments following concussion, postural stability during dual-task gait remains understudied in this population.

Purpose
The purpose of this study was to evaluate the dual-task cost (DTC) in adolescents with an acute or chronic SRC compared to reference values from healthy athlete peers for spatiotemporal parameters of gait during walking with and without a concurrent visuospatial memory task presented on a hand-held tablet. Researchers hypothesized that adolescents during the acute phase of concussion would be likely to experience a greater DTC compared to healthy peers in at least one spatiotemporal parameter of gait when walking within the dual-task paradigm.

Study Design
Cross-sectional, observational cohort design

Methods
Adolescents with concussion were recruited to participate. Subjects were divided into acute and chronic categories based on significant differences in the neuropsychological function after a period of 28 days. They walked at a self-selected speed along the 5.186-meter GAITRite® Walkway System with and without a concurrent visuospatial cognitive task presented on a hand-held tablet. Outcomes included normalized velocity (m/s), step length (m), and double limb (DLS) and single limb support (SLS) (defined as the percent of a gait cycle [%GC]). The data were then compared to the previously published reference values established using the same methods in the healthy athlete participants for all spatiotemporal parameters of gait.

Results
Data was collected on 29 adolescent athletes with SRC. Among males (15.53+/−1.12 years) with SRC, 20% of acute and 10% of chronic cases experienced a greater DTC compared to healthy athlete reference values. A similarly increased DTC was experienced by 83% of acute and 29% of chronic SRC cases for females (15.58+/−1.16 years).

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Conclusions
Adolescent athletes with concussion may continue demonstrating deficits in gait capabilities even in the chronic phase, and compensatory gait strategies were not the same between males and females. Dual-task cost assessment using the GAITRite® may be a valuable adjunct to comprehensive analysis of gait following SRC.

Level of Evidence
2

INTRODUCTION
In a 2018 report to Congress, the Centers for Disease Control and Prevention (CDC) classified mild traumatic brain injuries (mTBI) among children aged 18 years and younger as a major public health burden.1 Sports are a leading source of concussion, a form of mTBI, with approximately 1.6 to 5.8 million sport-related concussions (SRC) occurring each year.2 Athletes in the adolescent age group of 10 to 19 years comprise the largest athletic cohort at nearly 44 million participants annually.3 Additionally, nearly 70% of all SRC cases in the United States were reported among adolescent athletes.4 As a response to the growing rate of emergency department visits secondary to concussion among adolescents,5 concussion management groups including the American Medical Society for Sports Medicine (AMSSM)6 and Concussion in Sport Group (CISG)7 have promulgated recommendations for improvements in the recognition, diagnosis, rehabilitation, treatment, and overall mitigation of SRC.

The most common symptoms following SRC in adolescent athletes include deficits in somatic, vestibular, ocular, and cognitive systems as well as abnormalities in emotional regulation and sleep.6,7 Postural instability has been identified as a hallmark of SRC8,9 and authors have established that prolonged dizziness, reported in approximately 65-75% of athletes with concussion, is most predictive of protracted recovery.10 For this reason, multimodal sideline assessment batteries assess a variety of symptom characteristics as well as neuromotor capabilities.2,6–8 Specifically, researchers have shown that SRCs commonly disrupt important neurological processes that allow for communication between the vestibular system, cerebellum, and motor cortex, which play critical concerted roles in controlling posture and balance during gait.9,11 Although previous authors have reported that neurocognitive impairments persist beyond subjective symptom resolution, dynamic motor tasks such as gait following concussion may not be adequately assessed clinically.11

Authors exploring deficits in gait among athletes with SRC have shown that no significant differences exist when compared to healthy controls while ambulating alone.12,13 In contrast, researchers have identified deficits in neuromotor capabilities athletes of varying ages with and without concussion during walking within a dual-task paradigm, which combines cognitive and motor demands.14–19 Additionally, a significant dual-task cost (DTC), or the relative change between single-task and dual-task performance,14 has been reported for specific spatiotemporal parameters of gait, including gait speed,15,16–20 stride length,12–14,16,17 step length,18,20 double limb support time (DLS),16,18–20 and single limb support time (SLS18–20 in athletes with and without concussion using computerized technology. Howell et al21 previously reported good to excellent consistency for DTCs when assessing adolescents during single- and dual-task walking, concluding that healthy controls are effective comparators when assessing subjects with injury. Cognitive tasks incorporated into dual-task gait paradigms have challenged different constructs of cognition, memory, and coordination. The Mini-Mental Examination (MMSE), Auditory Stroop Test, and Brooks Visuospatial Memory Task, which incorporate constructs of memory, auditory perception, and recall, have been used to demonstrate that significant differences in gait parameters exist between adolescents with and without SRC in dual-task, but not always single-task, gait paradigms.12,13,21,22 Authors examining dual-task gait paradigms have also established normative reference values for adolescent athletes using varying methodologies and cognitive tasks, which have provided great insight into remaining deficits even after symptom resolution; however, many studies lack a closed environment mirroring aspects of athletic play wherein athletes’ attention is focused on a manipulable hand-held object during gait.

Ambulation while manipulating a hand-held object, such as a phone or sports ball, is commonplace in daily activities (e.g., maneuvering through class or school spaces while texting) and athletic play (e.g., catching or focusing on a ball in football or soccer, among other sports, while running in a specific direction). In 2018, Howell et al25 revealed that collegiate athletes with a history of concussion demonstrated significantly decreased walking speed during dual-task gait with neurocognitive tests presented on a hand-held tablet compared to healthy controls. Furthermore, in 2019, Lowe et al20 established baseline data for healthy adolescent athletes during single-task gait without a cognitive component and dual-task gait using a hand-held tablet to perform a visuospatial memory task while walking along the GAITRite® Walkway System. In that study, authors found that both male and female healthy athletes experienced a significant DTC (p<0.0001) for gait velocity, step length, DLS, and SLS.20 However, data for concussed adolescents combining a motor and cognitive (visuospatial memory) task with altered visual attention has not been published. An altered, or larger than expected DTC during a combined motor and cognitive task post-concussion could pose a risk to adolescents returning to daily activity and especially athletic play.24 Studies have highlighted the complexity of concussion as a formal diagnosis given variability in symptomology and recovery time-
frames.\textsuperscript{1,2} Despite the existence of widely adopted return to play (RTP) protocols based on symptomology, no consensus has been reached regarding the consistent assessment of postural stability during gait. Therefore, examining DTC may be a viable and insightful addition to comprehensive assessments of concussion.

Compensatory strategies may not be entirely consistent between individual athletes with SRC.\textsuperscript{25} Given that individuals with concussion often present with such a variety of compensatory mechanisms during movement, the authors of the current study believe it is essential to examine athletes individually while assessing multiple parameters. For the purpose of the current study, authors focused on normalized velocity (m/s), step length (m), and SLS and DLS as a percentage of a gait cycle (%GC), which may present quite differently from one injured athlete to the next. Consistent with common methodologies in physical therapy for assessing children with deficit,\textsuperscript{26} the chosen cutoff for considering a parameter to be of concern and warrant further attention is one standard deviation (SD). Specifically, the outcome measure of interest was the DTC experienced by adolescent athletes with SRC on each spatiotemporal parameter of gait.

Therefore, the purpose of this study was to evaluate the DTC in adolescents with an acute or chronic SRC compared to reference values from healthy athlete peers\textsuperscript{22} for spatiotemporal parameters of gait during walking with and without a concurrent visuospatial memory task presented on a hand-held tablet. Researchers hypothesized that adolescents during the acute phase of concussion and seeking a medical evaluation or follow-up would be likely to experience a DTC greater than one SD compared to healthy athlete peers in at least one spatiotemporal parameter of gait when walking within the dual-task paradigm. This study also aimed to explore any residual deficits compared to their healthy athlete peers that might present during the chronic phase of concussion that could aid in RTP decisions.

METHODS

PARTICIPANTS

A convenience sample of 29 athletes, between the ages of 14-18 years old, with documented SRC was recruited from a regional sports medicine concussion clinic. The Institutional Review Board at the University of Arkansas for Medical Sciences approved the study. All participants and guardians provided written informed consent to participate in the study. Participants were included in the study if they were being treated at a regional sports medicine clinic for a sport related concussion, had participated in sport programs through their school, were between the ages of 14-18 years old, and had a completed informed consent from the parent/guardian. Participants were excluded if they had a recent lower extremity injury or were deemed medically unfit to participate in assessments by the clinic sports medicine physician. Using the protocol outlined below, participants were assessed at each clinic visit until discharge (minimum of one and maximum of three assessments).

Therefore, an individual participant in the current study could contribute up to three assessments if that participant continued to be seen in the clinic for a protracted recovery. Data from these assessments were divided into acute and chronic categories based on significant differences in neuropsychological function after a period of 28 days.\textsuperscript{27}

PROTOCOL

Gait parameters were assessed by instructing the participants (n=29) to walk at a self-selected speed on the 5.186 meters long GAITRite\textsuperscript{®} (CIR Systems, Inc.; Franklin, NJ) portable gait analysis walkway for three undivided attention trials in addition to three divided attention trials. During each divided attention trial, a visuospatial memory task was given to the subjects to complete on a tablet (Microsoft Surface Pro, 2016) while walking. Participants used a tablet rather than their own cell phones to achieve novelty and require attention to the device. The task (Pattern Memory by ProProfs.com, available at www.memory-improvement-tips.com), similar to the visuospatial memory tasks commonly included in the neurocognitive testing used in concussion management, consisted of a one-second period of time to view a pattern of shapes arranged spatially on the tablet screen. After this time period, the shapes disappeared. The participants then had to place the shapes in the original position relying upon visuospatial working memory. Participants who typically wear corrective eyewear (e.g., glasses or contact lens) wore them during the assessment. All participants performed this task in the same manner with three practice attempts to learn the task in static stance and data collection during gait beginning at level four of the task. Additionally, the participants initiat ed the task 2.5 meters prior to stepping onto the pathway to allow the task to continue throughout the entirety of the sensor pathway and to account for acceleration. Investigators monitored each trial to ensure that the participant was actively completing the task throughout the data recording time period. If the participant failed at the task, causing the game to discontinue during a trial, that trial was repeated to ensure that the participant was actively completing the task throughout.

The GAITRite\textsuperscript{®} portable gait analysis walkway and the corresponding GAITRite\textsuperscript{®} software were used to record temporal and spatial parameters. Prior to each participant’s trials, investigators entered data for leg length, which was measured as the distance from greater trochanter to floor for each leg. For the purposes of this study, parameters that were captured by the GAITRite\textsuperscript{®} include: gait velocity (cm/s); step length (cm); DLS, defined as the percent of the gait cycle (%GC) when both feet are on the ground; and SLS, defined as the %GC weight bearing through a single limb. The walkway is 5.186 meters long and embedded with sensors recording footfall pressures at 80 Hz, which allows calculation of temporal and spatial markers of gait. The software averages the three gait trials under each walking condition providing means for each parameter. The GAITRite\textsuperscript{®} system has been shown to be a reliable and valid measure of gait for healthy individuals.\textsuperscript{28}
Table 1. Participant demographics by sex, race, and ethnicity.

<table>
<thead>
<tr>
<th>Race</th>
<th>Males (n=17)</th>
<th>Females (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>African American</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2 or More</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethnicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hispanic</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-Hispanic</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

Additionally, 10% of male and 29% of female chronic assessments demonstrated a DTC greater than one SD compared to healthy athletes. For the 10% of male participants assessed in the chronic phase, the increased DTC was experienced in DLS only (Figure 1b). For the female participants assessed in the chronic phase, the higher DTC was distributed across the four parameters (Figure 2b).

**DISCUSSION**

The present study adds important insight into the need for comprehensive clinical assessments of gait in adolescent athletes with SRC. Lingering deficits in dynamic balance during stance have been previously identified by the current authors utilizing clinical assessments of balance. Additionally, for the past decade, the literature has highlighted the importance of assessing dual-task gait among adolescent, collegiate, and adult athletes. Moreover, healthy reference values and DTCs have been frequently used to assess adolescent athletes with concussion when exploring the impact of dual-task paradigms on spatiotemporal parameters of gait. The current study contributes novel findings suggesting that varying compensatory mechanisms exist in male and female adolescent athletes with acute or chronic SRC when combining a cognitive and gait task, further promoting the use of the DTC as a viable adjunct assessment following SRC.

Results from the present study reveal that a considerable number of male and female cases with acute concussion, approximately three out of 15 male assessments and five out of six female assessments, experienced a DTC greater than one SD compared to peers without injury. This finding is similar to those of previous studies that have revealed significant differences between healthy adolescent athletes and those with concussion (typically tested within 10 days after injury) in several spatiotemporal parameters of gait. The current study also found that the increased DTC was not experienced for the same spatiotemporal parameters of gait or to the same degree by males and females with acute SRC, suggesting that different compensatory patterns to perform dual-task gait may be evident based on sex in similar samples. Recently, Kieffer et al. found that even in collegiate athletes, who are presumed to function with more developed neuromuscular abilities, DTCs for several parameters of gait varied irrespective of sex but were overall higher for females. When assessing adolescent athletes within 14 days of concussion, Howell et al. found that females typically experienced a significantly greater DTC for cadence (not measured in the current study), whereas a separate study reported inconsistent variability in several cognitive, neuromotor, and oculomotor functions according to sex. With respect to varying gait strategies, Table 4 provides valuable data for individual assessments by each participant during initial testing who experienced a DTC greater than one SD compared to healthy references in at least one parameter of gait. Male participant A and female participant B, both with acute SRC, experienced the DTC on at least three parameters, representing athletes with the most negative side effects.
Table 2. Table 2 published by Lowe et al.\textsuperscript{20} demonstrating "the means and standard deviations of the gait parameters when [healthy] subjects walked without a concurrent visual-cognitive task (Single-Task) and with a concurrent visual-cognitive task (Dual Task). The means and standard deviations for the dual-task cost for each parameter (DTC)."

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single Task</th>
<th>Dual Task</th>
<th>DTC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>1.236</td>
<td>1.449</td>
<td>1.030</td>
</tr>
<tr>
<td>(0.163)</td>
<td>(0.199)</td>
<td>(0.185)</td>
<td>(0.196)</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>68.031</td>
<td>65.483</td>
<td>60.073</td>
</tr>
<tr>
<td>(6.779)</td>
<td>(6.021)</td>
<td>(7.858)</td>
<td>(5.885)</td>
</tr>
<tr>
<td>% in DLS</td>
<td>29.077</td>
<td>26.922</td>
<td>31.92</td>
</tr>
<tr>
<td>(2.631)</td>
<td>(2.648)</td>
<td>(3.461)</td>
<td>(3.085)</td>
</tr>
<tr>
<td>% in SLS</td>
<td>35.390</td>
<td>36.522</td>
<td>34.05</td>
</tr>
<tr>
<td>(1.504)</td>
<td>(1.352)</td>
<td>(1.901)</td>
<td>(1.549)</td>
</tr>
</tbody>
</table>

*Statistically significant DTC at p<0.0001

Table 3. Percentage of male (25 assessments) and female (20 assessments) acute and chronic cases that experienced a DTC at least one SD greater than those of healthy subjects from the study by Lowe et al.\textsuperscript{20} in each of the spatiotemporal parameters of gait recorded using the GAITRite® Walkway System.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Males (n = 25 assessments)</th>
<th>Females (n = 20 assessments)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acute %</td>
<td>Chronic %</td>
</tr>
<tr>
<td></td>
<td>Cases (n=15*)</td>
<td>Cases (n=10*)</td>
</tr>
<tr>
<td>Normalized Velocity</td>
<td>20%</td>
<td>0%</td>
</tr>
<tr>
<td>Step Length</td>
<td>13%</td>
<td>0%</td>
</tr>
<tr>
<td>SLS (%GC)</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td>DLS (%GC)</td>
<td>7%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Asterisk (*) denotes the percentage of the male and female acute (20% and 83%, respectively) and chronic (17% and 30%, respectively) cases that experienced a DTC greater than one SD compared to healthy athlete reference values for at least one spatiotemporal parameter of gait.

Figure 1. Percentage of male acute (1a; three out of 15) and chronic (1b; one out of 10) cases that experienced a DTC at least one SD greater than those of healthy athletes from the study by Lowe et al.\textsuperscript{20} in each of the spatiotemporal parameters of gait.
of a concussion who may require personalized balance and gait training in addition to eventually progressing through a RTP protocol. Perhaps more alarming was the presence of participants who were already classified as having chronic SRC at initial testing, namely female participants E and H, and still experiencing a higher DTC than references on at least one parameter of gait. This finding suggests that a classification of chronicity and perhaps symptom resolution may not be sufficient alone in determining an athlete’s readiness to safely return to sport.

The current study also revealed further inconsistencies in the progression of biomechanical strategies for gait in a dual-task paradigm after participants still in the concussion clinic surpassed the threshold for chronicity (>28 days) during follow-up testing. Table 5 provides information for male and female athletes with chronic SRC who continued to experience a DTC greater than one SD compared to healthy athlete controls. Female participants D and G experienced a DTC within one SD compared to healthy athletes in normalized velocity during the acute phase (Table 4), but then demonstrated a DTC higher than one SD for the same parameter after meeting the threshold for chronic classification. Given that slowed average gait speed has been highly correlated with concussion severity and prolonged recovery after SRC,14,17,24 special attention may be warranted for athletes with elevated DTCs in this parameter. Additionally, although male participant B improved the DTC of his average gait speed and step length, he may have shifted his compensatory strategy to DLS, as evidenced by an increased DTC during the chronic phase (Table 4 and 5). These scenarios of fluid compensatory strategies were not consistent for each participant and varied between males and females; however, athletes like participants B, D, and G, who continued to experience gait deficits 28 days after initial injury, may be at higher risk for reinjury even after progressing through a symptom based RTP protocol.

Modern protocols suggest that, on average, symptom resolution may occur as soon as seven to 10 days following SRC, and most graduated RTP programs progress student athletes back to physical activity mainly guided by subjective symptom resolution.2,6 However, other researchers have identified athletes who reported symptom resolution after 21 to >28 days of initial injury and continued to either walk with significantly slower average gait speeds, smaller cadences, and shorter stride lengths or experience significant DTCs compared to healthy controls. Furthermore, Howell and colleagues24 found that adolescent athletes who experienced reinjury after RTP had consistently demonstrated a significant gait speed DTC across time, similar to participants D and G from our study. Therefore, it is evident that more work needs to be done to adequately assess postural stability in gait for adolescent athletes after SRC in addition to symptoms based RTP protocols. Currently, there is no consensus on a viable tool for assessing spatiotemporal parameters of gait following concussion. Based on the findings of the current study, the GAITRite® Walkway System combined with DTC assessment may provide data valuable in identifying deficits in gait that may otherwise go undetected by multimodal assessments such as the Sport Concussion Assessment Tool (SCAT-third or fifth edition), which assesses subjective aspects of ambulation and limited constructs of postural stability during a tandem gait test.2,6

**LIMITATIONS**

This study used a sample of convenience in a relatively small group of adolescents with a narrow age range. Ideally, all athletes would have been assessed first during the acute phase of SRC and again in a progressive manner throughout the chronic stage. Additionally, not all athletes were able to contribute to assessments beyond initial testing, either due to worsening symptoms or meeting criteria to initiate a RTP protocol.
Table 4. Subjects with a DTC greater than one SD compared to published values for at least one parameter at initial assessment for the current study.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Acuity</th>
<th>Normalized Velocity</th>
<th>Step Length</th>
<th>SLS (%GC)</th>
<th>DLS (%GC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Single</td>
<td>Dual</td>
<td>DTC</td>
<td>Single</td>
</tr>
<tr>
<td>A</td>
<td>Male</td>
<td>Acute</td>
<td>0.9*</td>
<td>0.53*</td>
<td>0.37†</td>
<td>63.16</td>
</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>Acute</td>
<td>1.2</td>
<td>0.78*</td>
<td>0.42†</td>
<td>68.03</td>
</tr>
<tr>
<td>C</td>
<td>Male</td>
<td>Acute</td>
<td>1.16</td>
<td>0.8</td>
<td>0.36†</td>
<td>62.75</td>
</tr>
<tr>
<td>D</td>
<td>Female</td>
<td>Acute</td>
<td>1.22</td>
<td>0.89*</td>
<td>0.33</td>
<td>62.4</td>
</tr>
<tr>
<td>E</td>
<td>Female</td>
<td>Chronic</td>
<td>1.86</td>
<td>1.1</td>
<td>0.76</td>
<td>79.63</td>
</tr>
<tr>
<td>F</td>
<td>Female</td>
<td>Acute</td>
<td>0.86*</td>
<td>0.64*</td>
<td>0.32</td>
<td>52.09*</td>
</tr>
<tr>
<td>G</td>
<td>Female</td>
<td>Acute</td>
<td>1.19*</td>
<td>0.85*</td>
<td>0.34</td>
<td>60.69</td>
</tr>
<tr>
<td>H</td>
<td>Female</td>
<td>Chronic</td>
<td>1.08*</td>
<td>0.75*</td>
<td>0.33</td>
<td>61.23</td>
</tr>
<tr>
<td>I</td>
<td>Female</td>
<td>Acute</td>
<td>1.38</td>
<td>1.0</td>
<td>0.38†</td>
<td>63.29</td>
</tr>
<tr>
<td>J</td>
<td>Female</td>
<td>Acute</td>
<td>1.36</td>
<td>1.16</td>
<td>0.2</td>
<td>63.86</td>
</tr>
</tbody>
</table>

Values with * indicate either single- or dual-task trials that were at least one SD less compared to healthy athletes. Bolded values with † denote DTCs that were at least one SD greater than those of healthy athletes.

Table 5. Subjects with a DTC greater than one SD compared to published values for at least one parameter during follow-up assessment.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Acuity</th>
<th>Normalized Velocity</th>
<th>Step Length</th>
<th>SLS (%GC)</th>
<th>DLS (%GC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Single</td>
<td>Dual</td>
<td>DTC</td>
<td>Single</td>
</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>Chronic</td>
<td>1.44</td>
<td>1.14</td>
<td>0.3</td>
<td>77.48*</td>
</tr>
<tr>
<td>D</td>
<td>Female</td>
<td>Chronic</td>
<td>1.11*</td>
<td>0.76*</td>
<td>0.35†</td>
<td>61.91</td>
</tr>
<tr>
<td>G</td>
<td>Female</td>
<td>Chronic</td>
<td>1.25</td>
<td>0.89*</td>
<td>0.36†</td>
<td>59.01*</td>
</tr>
</tbody>
</table>

Values with * indicate either single- or dual-task trials that were at least one SD less compared to healthy athletes. Bolded values with † denote DTCs that were at least one SD greater than those of healthy athletes.
protocol. More robust studies with a longer duration and a sample population from more than one medical facility would contribute to improved generalizability of these findings. Furthermore, a more racially and ethnically diverse sample of adolescents with concussion would contribute to generalizability. Data collection was performed using an expensive piece of equipment, not readily available to most clinicians. Further research comparing data obtained using the same visuospatial memory task during gait with incorporation of more traditional and clinically feasible tools (e.g., 10 Meter Walk Test) could provide valuable and practical insight to more clinicians in a variety of settings. Additionally, the complexity of the visuospatial memory task was not customized to the subject’s individual cognitive or motor capacities. Therefore, given the broad potential impact of concussion on neurocognitive capabilities, the attention, detailed understanding, and processing of all testing requirements may have varied for each participant.

CONCLUSIONS

The findings of the current study support the continued need for comprehensive assessments of postural stability in gait for adolescent athletes with SRC. High variation in DTCs that were greater than one SD compared to healthy subjects for several spatiotemporal parameters of gait highlights the potential need for customized rehabilitation plans prior to eventual RTS. No two athletes in the limited sample of the current study demonstrated the same compensatory strategies, mitigation patterns, or potential deficits during single- and dual-task gait with a SRC classified as either acute or chronic in nature. DTC analysis using the GAITRite® Walkway System may be a valuable adjunct to current assessment strategies following concussion among adolescent athletes. However, given potential constraints regarding financial, set-up time, and training requirements for the GAITRite®, future work is warranted to explore viable clinical assessment tools and/or strategies with strong agreement with higher order technologies for evaluating spatiotemporal parameters of gait. Additionally, future studies may build upon the framework established by this preliminary study by incorporating longitudinal designs with assessment of all subjects at varying stages following concussion with inclusion of matched controls from similar schools.

CONFLICTS OF INTEREST

The authors have no conflicts of interest.

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REFERENCES


Muscle Strength, Oxygen Saturation and Physical Activity in Patients with Chronic Exertional Compartment Syndrome Compared to Asymptomatic Controls

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Keywords: Chronic Exertional Compartment Syndrome, Muscle Strength, Exercise-Induced Leg Pain, Oxygen saturation, Physical activity

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International Journal of Sports Physical Therapy

Background
One of the most common causes of exercise-induced pain in the lower leg is chronic exertional compartment syndrome (CECS). Research is limited on muscle strength, oxygen saturation and physical activity in patients with CECS.

Purpose
To compare muscle strength, oxygen saturation, and daily physical activity between patients with CECS and matched asymptomatic controls. A secondary purpose was to investigate the association between oxygen saturation and lower leg pain in patients with CECS.

Study Design
Case-control study.

Method
Maximal isometric muscle strength of the ankle plantar and dorsiflexors was tested in patients with CECS and sex- and age-matched controls using an isokinetic dynamometer and oxygen saturation (StO₂) during running was tested by near infrared spectroscopy. Perceived pain and exertion were measured during the test using the Numeric Rating Scale and Borg Rating of Perceived Exertion scale and the exercise-induced leg pain questionnaire. Physical activity was assessed by accelerometry.

Results
Twenty-four patients with CECS and 24 controls were included. There were no differences in maximal isometric plantar or dorsiflexion muscle strength between patients and controls. Baseline StO₂ was 4.5pp (95% CI: 0.7;8.3) lower for patients with CECS than for controls, whereas no difference existed when they experienced pain or reached exhaustion. No differences were found in daily physical activities, except that on average, patients with CECS spent less time cycling daily. During the StO₂ measurement, patients experienced pain or reached exhaustion while running significantly earlier than the controls (p<0.001). StO₂ was not associated with leg pain.

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Conclusion
Patients with CECS have similar leg muscle strength, oxygen saturation and physical activity levels as asymptomatic controls. However, patients with CECS experienced significantly higher levels of lower leg pain than the controls during running, daily activities and at rest. Oxygen saturation and lower leg pain were not associated.

Level of Evidence
Level 3b.

INTRODUCTION

One of the most common causes of exercise-induced pain in the lower leg is chronic exertional compartment syndrome (CECS). The cause of this syndrome has been debated and is still not fully clarified. CECS has been defined as pain due to exertion-increased muscle compartment pressure, causing tissue perfusion and ischemic pain. Symptoms include cramping pain, paresthesia and muscle weakness. Most often, the anterior compartment is affected, but the deep posterior compartment, the lateral compartment and the superficial posterior compartment may also be affected. CECS has been described as a problem exclusively in athletes, but the condition has also been observed in both nonathletic individuals as well as in individuals with a sedentary lifestyle. Running and walking were reported as the main activity causing pain among 36 patients with CECS.

The CECS diagnosis relies on a medical history of exercise-induced pain in the lower leg with symptom resolution after exercise cessation, and CECS may further be accompanied by increased intramuscular pressure after exercise. The intra-compartmental pressure can be measured using a needle or catheter inserted into the muscular compartment. However, this is an invasive and painful intervention, and near-infrared spectroscopy (NIRS) has been suggested as a non-invasive alternative allowing assessment of tissue oxygen saturation (StO₂) and muscle hemodynamics in both patients and healthy populations.

First-line treatment for CECS includes reduced exercise volume, gait alteration, running alteration and/or strengthening exercises. If a conservative approach fails, CECS can be treated surgically with subcutaneous fasciotomy. A recent systematic review based on 68 studies evaluated results of a total of 3783 patients of whom 95% were surgically treated for CECS. The review found an overall satisfaction rate of 85% after surgery compared to a satisfaction rate after conservative treatment of 47%. The overall return to physical activity rate was 80% after surgery and 50% after conservative treatment. Thus, further studies aiming to identify potential physiological treatment targets in patients with CECS are highly warranted.

The primary aim of the study was to compare muscle strength, StO₂ and physical activity among patients with CECS and a group of sex- and age-matched asymptomatic controls. It was hypothesized that patients with CECS would have (i) higher maximal muscle strength in the plantar and dorsiflexion of the ankle joints, (ii) lower StO₂ in the affected compartment during running and (iii) higher daily physical activity levels compared to a group of sex- and age-matched asymptomatic controls. The secondary aim was to investigate any association between oxygen saturation and lower leg pain.

METHODS

The present case-control study compared a group of patients with CECS and a group of sex- and age-matched asymptomatic controls. The study was conducted in accordance with the Helsinki declaration. The design, aim and procedures were presented to the local research ethics committee (record number: 183/2018). According to Danish law, no ethics approval was needed for this type of study. The Danish Data Protection Agency approved handling of personal data (record number: 1-16-02-181-19), and all included participants provided written consent prior to data collection.

PATIENTS

Patients with suspected CECS were recruited at Department of Orthopaedic Surgery at Aarhus University Hospital between November 2019 and June 2021. Inclusion criteria were unilateral or bilateral symptoms of CECS, such as intense anterior lower leg pain or intense tightness after approximately 10 minutes of physical activity, muscle cramps and/or decreased muscular function of one of the compartments in combination with pain. In addition, symptoms had to have persisted for three months, and symptoms had to be normalized within ~30 minutes of exercise cessation. Patients were excluded if they demonstrated symptoms of nerve or artery entrapment, lumbar spine disease, muscle herniation, tibial stress fracture, or tibial stress syndromes. As the NIRS technology might be less accurate in patients with highly pigmented skin or a fat layer of more than 4 cm subcutaneous at the testing area, these patients were excluded from the study after assessment.

ASYMPTOMATIC CONTROLS

Asymptomatic controls were recruited by advertisements at the educational institution VIA University College, Aarhus University Hospital and through social media. Controls were matched by sex and age (+/- 5 years) with patients with CECS and were able to read and understand Danish. Controls were not considered eligible if they (i) had been diagnosed with CECS, (ii) had a chronic disease or a musculoskeletal injury affecting their gait or muscle function, (iii) were undergoing elective surgery in the lower extremities within the next six months, (iv) had undergone surgery in...
the lower extremities within the prior two years or (v) were pregnant.

TEST PROCEDURE

Patients and controls were tested by a physiotherapist or an exercise physiologist trained in the test procedure at Department of Public Health, Aarhus University. Weight was measured using a Tanita weight (SC-330MA, Tanita Corporation of America, Illinois, USA), and height was measured using a telescopic height measuring device from ADE (MZ10023, DES Germany GmbH, Hamburg, Germany).

ISOMETRIC MUSCLE STRENGTH

Maximum voluntary isometric contraction of the plantar and dorsiflexors of the foot was measured in an isokinetic dynamometer (Humac Norm CSMI, Stoughton, Massachusetts, USA). Motor-driven dynamometry has been described as the gold standard in assessment of muscle strength.10 Isometric plantar flexion was tested first, starting with the contralateral leg, followed by dorsiflexion of the same leg (Figure 1). The test was performed with the patient in a prone position, without shoes and with the knee in 0°. The dynamometer rotation axis was aligned with the lateral malleolus on the tested leg when the foot was in a neutral position (0°). Plantar flexion was tested in this position, while dorsiflexion was tested in 25° plantar flexion. Patients and controls were instructed to press against the dynamometer pad with as much force and as fast as possible for about four seconds. Subsequently, isometric plantar flexion followed by dorsiflexion was tested in the affected/paired leg. Between each attempt, a rest period of 30 seconds was provided. To correct for gravity, the weight of the leg was measured for each movement. One test attempt was made followed by at least three maximum voluntary contraction attempts. If an improvement of more than 10% in the last attempt was detected, an additional attempt was performed. However, a maximum of five attempts was completed to avoid muscle fatigue. A test-retest was performed for the first six patients. The intraclass coefficient (ICC) was 0.92 (95% CI: 0.66;0.98) for the measure of plantar flexion and 0.77 (95% CI: 0.24;0.95) for dorsiflexion in the affected leg. For the nonaffected leg, the ICC was 0.77 (95% CI: 0.26;0.95) for plantarflexion and 0.76 (95% CI: 0.18;0.95) for dorsiflexion.

NEAR-INFRARED SPECTROSCOPY

\( \text{StO}_2 \) was measured using NIRS. The PortaMon, a wearable wireless NIRS unit (Artinis Medical System, Elst, The Netherlands), was placed on the affected leg at the affected compartment in patients and on the right leg at the matched compartment in controls (Figure 1). First, fibula length was measured, and 1/3 of the fibula length was marked distal from the head of the fibula. If the anterior compartment was affected, the PortaMon was placed 2 cm laterally from the forward facing bone margin (margo anterior) on tibia and in line with the mark on fibula. If the lateral compartment was affected, the PortaMon was placed 6 cm laterally from margo anterior on tibia and in line with the mark on fibula. If the posterior superficial compartment was affected, the PortaMon was placed on the muscle belly of the medial gastrocnemius. The area was shaved and cleansed before placing the PortaMon with two bandages to keep free of light. Data were collected using the OxySoft software (Artinis Medical System, Elst, The Netherlands). All participants were instructed to run on a treadmill starting at 10 km/hour. The speed was increased by 1 km/hour every two minutes until the patients experienced intense recognizable leg pain or reached exhaustion. Information on perceived pain and exertion was obtained using a Numeric Rating Scale (NRS)11 and the Borg Rating of Perceived Exertion scale12 every minute. The test was terminated for controls when they reached exhaustion. Patients and controls were then instructed to sit down and relax for 10 min. while still measuring \( \text{StO}_2 \). During the test, the timepoints for starting, stopping, and terminating the test were registered in the OxySoft software. After the test, baseline \( \text{StO}_2 \) was registered as an average of 15 \( \text{StO}_2 \) registrations prior to the baseline mark and peak \( \text{StO}_2 \) as an average of 15 \( \text{StO}_2 \) registrations prior to the stop mark and the absolute and relative (percentage) change was calculated.13 A test-retest was performed for the first six patients. The ICC was 0.73 (95% CI: 0.02;0.96) for the measure of baseline \( \text{StO}_2 \) and 0.92 (95% CI: 0.59;0.99) for the peak exercise \( \text{StO}_2 \). NIRS has been found to be a valid and reliable noninvasive measurement to measuring \( \text{StO}_2 \) and diagnose CECS, compared to intracompartmental pressure, with a sensitivity of 85%.4

PHYSICAL ACTIVITY

Daily physical activity was measured using tri-axial accelerometry by placing an accelerometer (AX5 Axity Ltd., Newcastle, UK) on the lateral side of the thigh, at half the
distance from the major trochanter to the lateral femoral condyle, on the affected leg in patients and on the right leg in controls (Figure 2). The accelerometers were small wearable sensors measuring acceleration in three dimensions at 100 Hz. Patients and controls were asked to wear the accelerometer for seven consecutive days following the physical tests and to remove the accelerometer at night. Each day, patients registered information on when they had put on and removed the accelerometer and whether it had been removed during the day. In the same logbook, the patients rated their daily level of pain during rest and activity on a 100-millimetre-long visual analogue scale (VAS). The accelerometer and the logbook were returned to the hospital and data was downloaded using the OMGUI Configuration and Analysis Tool (Version 1.0.0.43, Newcastle, UK). Data were split into days and analysed using a validated algorithm to identify different types of activities based on the average magnitudes of the three acceleration vectors and the gait cycle frequency. Furthermore, an intensity parameter was constructed, grouping each 10-second data window into one of the following categories; (i) very low intensity activity (0-0.05 g) e.g., sitting or standing, (ii) low intensity activity (0.05-0.1 g) e.g., standing or shuffling, (iii) moderate intensity activity (0.1-0.2 g) e.g., slow or normal walking and (iv) high intensity activity (>0.2 g) e.g., fast walking, running or jumping. Days containing less than 10 hours of data were excluded. To describe the daily physical activity collected with accelerometers, the four dimensions of physical activity according to the World Health Organization (WHO): Frequency, Intensity, Time and Type (F.I.T.T.) were used.

THE EXERCISE-INDUCED LEG PAIN QUESTIONNAIRE

The exercise-induced leg pain questionnaire (EILP) was originally developed for German-speaking patients (EILP-G) with exercise-induced leg pain such as CECS, medial tibial stress syndrome and stress fractures. The German version of the questionnaire has been found to have excellent reliability, with an Intraclass Correlation Coefficient ranging from 0.86-0.99, as well as good face and construct validity to measure the severity of symptoms and functional limitations for patients with exercise-induced leg pain. The questionnaire consists of 10 items scored on a five-point Likert scale ranging from no difficulty to unable to do (0-4). The total score was calculated by dividing the sum score with the maximum possible points and then converted to a score from 0-100, where 0 indicated severe problems and 100 indicated no problems. A Danish version of the questionnaire was used, translated in accordance with international standards and approved by the authors of the original German version.

STATISTICAL ANALYSIS

Categorical variables were presented as numbers with percentages and analysed using the chi-squared test. Continuous variables were presented as means with 95% confidence intervals (95% CI) if normally distributed, otherwise as medians with interquartile ranges (IQR). The assessment of normality was performed using probability plots and histograms. Comparisons between the two groups were made using the student t-test when data were normally distributed, and the Mann-Whitney U test was used to compare the not normally distributed EILP-D and VAS scores between groups. The Spearman’s Rank Correlation Coefficient assessed associations between StO₂ and lower leg pain. Correlations were interpreted as follows: a correlation >0.90 was interpreted as very strong, 0.70-0.89 as strong, 0.50-0.69 as moderate, 0.30-0.49 as weak and <0.29 as low. All statistical analyses were performed in Stata version 17.0 (StataCorp LLC, College Station, TX, USA).

RESULTS

Twenty-four patients with CECS and 24 age- and sex-matched controls were included in this study. Characteristics of patients and controls are presented in Table 1.

ISOMETRIC MUSCLE STRENGTH

There were no significant differences between the two groups in either isometric plantar or dorsiflexion, nor in the affected/matched leg or the contralateral leg (Table 2). In addition, the difference between the affected and the contralateral leg in plantarflexion for patients with CECS was 1.8 Nm (95% CI -10.3;14.0), though not statistically significant (p=0.76). The difference was 0.6 Nm (95% CI -2.4;3.5) for dorsiflexion, which was not statistically significant (p=0.69).

OXYGEN SATURATION

The baseline StO₂ in the affected or matched compartment was 4.5pp (95% CI: 0.7;8.3) lower for patients with CECS compared with controls (Table 2). The peak exercise StO₂ was similar for the two groups as the mean peak exercise StO₂ was 51.4% (SD 11.2) for patients and 52.9% (SD 16.7) for controls. There were no significant differences in the ab-
solute and relative change scores between the two groups (Table 2). However, the treadmill running time during the test was 3.5 minutes (95% CI: 1.7;5.3) lower for patients compared with controls.

**Table 1. Participant characteristics.**

<table>
<thead>
<tr>
<th></th>
<th>Patients with CECS</th>
<th>Controls</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants, n (%)</td>
<td>24 (100)</td>
<td>24 (100)</td>
<td></td>
</tr>
<tr>
<td>Males, n (%)</td>
<td>14 (58)</td>
<td>14 (58)</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>27 (8.0)</td>
<td>27 (6.6)</td>
<td>0.68</td>
</tr>
<tr>
<td>Height (cm), mean (SD)</td>
<td>177.6 (7.6)</td>
<td>176.6 (10.6)</td>
<td>0.68</td>
</tr>
<tr>
<td>Weight (kg), mean (SD)</td>
<td>79.7 (11.7)</td>
<td>77.3 (13.3)</td>
<td>0.50</td>
</tr>
<tr>
<td>BMI (kg/m²), mean (SD)</td>
<td>25.2 (2.7)</td>
<td>24.7 (2.9)</td>
<td>0.53</td>
</tr>
<tr>
<td>Right leg was affected, n (%)</td>
<td>17 (71)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previously undergone fasciotomy, n (%)</td>
<td>4 (20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheduled for fasciotomy after participating in the study, n (%)</td>
<td>11 (21)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Localisation of compartment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior compartment of the leg, n (%)</td>
<td>7 (29)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral compartment of the leg, n (%)</td>
<td>3 (13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior superficial compartment of the leg, n (%)</td>
<td>14 (58)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patient-reported leg pain EILP-D score, median (IQR)</td>
<td>60 (52.5;67.5)</td>
<td>100 (91.1;100)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VAS in rest, median (IQR)</td>
<td>9 (4.18)</td>
<td>0 (0.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>VAS in activity, median (IQR)</td>
<td>24 (15;36)</td>
<td>0 (0.0)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>


**Table 2. Isometric muscle strength of plantar and dorsiflexion, and Near Infrared Spectroscopy measurement of oxygen saturation in patients with chronic exertional compartment syndrome and controls.**

<table>
<thead>
<tr>
<th></th>
<th>Patients with CECS</th>
<th>Controls</th>
<th>Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean (SD)</td>
<td>n</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Isometric muscle strength, Nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantar flexion, affected/matched leg</td>
<td>24</td>
<td>109.2 (46.5)</td>
<td>24</td>
<td>115.0 (41.4)</td>
</tr>
<tr>
<td>Plantar flexion, contralateral leg</td>
<td>24</td>
<td>107.3 (35.6)</td>
<td>24</td>
<td>93.9 (42.3)</td>
</tr>
<tr>
<td>Dorsiflexion, affected/matched leg</td>
<td>24</td>
<td>42.1 (10.8)</td>
<td>24</td>
<td>37.4 (9.3)</td>
</tr>
<tr>
<td>Dorsiflexion, contralateral leg</td>
<td>24</td>
<td>41.5 (10.2)</td>
<td>24</td>
<td>41.2 (8.4)</td>
</tr>
<tr>
<td>Near Infrared Spectroscopy (NIRS) measurement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline StO₂ %</td>
<td>24</td>
<td>64.3 (5.4)</td>
<td>22</td>
<td>68.8 (7.4)</td>
</tr>
<tr>
<td>Peak exercise StO₂ %</td>
<td>24</td>
<td>51.4 (11.2)</td>
<td>22</td>
<td>52.9 (16.7)</td>
</tr>
<tr>
<td>Absolute change StO₂ %</td>
<td>24</td>
<td>13.0 (8.6)</td>
<td>22</td>
<td>16.0 (13.9)</td>
</tr>
<tr>
<td>Relative change StO₂ %</td>
<td>24</td>
<td>20.5 (13.4)</td>
<td>22</td>
<td>23.7 (20.5)</td>
</tr>
<tr>
<td>Time from start to end of test, min.</td>
<td>24</td>
<td>5.9 (3.0)</td>
<td>22</td>
<td>9.4 (3.1)</td>
</tr>
<tr>
<td>NRS at the end of the running test</td>
<td>24</td>
<td>5.6 (2.6)</td>
<td>22</td>
<td>0.8 (1.4)</td>
</tr>
<tr>
<td>Borg at the end of the running test</td>
<td>24</td>
<td>15.8 (2.5)</td>
<td>22</td>
<td>18.3 (2.1)</td>
</tr>
</tbody>
</table>

Abbreviations: CECS: chronic exertional compartment syndrome; NRS: Numeric Raking Scale. StO₂: oxygen saturation.

**PHYSICAL ACTIVITY**

Unfortunately, four patients did not return the accelerometers and these patients were thus excluded from the analysis of physical activity. In addition, two days of physical activity measurement from two patients with CECS and seven days from seven controls were excluded as these days contained less than 10 hours of data collection (range 2.5-9.9 hours).
Table 3. Daily physical activity levels in patients with chronic exertional compartment syndrome and controls described by the WHO dimensions of F.I.T.T.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Patients with CECS</th>
<th>Controls</th>
<th>Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
<td><strong>Mean (SD)</strong></td>
<td><strong>Mean (SD)</strong></td>
<td><strong>Mean (95% CI)</strong></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steps total, n</td>
<td>7257 (2087)</td>
<td>7982 (1876)</td>
<td>-725 (-1931;481)</td>
<td>0.23</td>
</tr>
<tr>
<td>Intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average cadence, steps/min</td>
<td>94.9 (7.1)</td>
<td>92.6 (8.9)</td>
<td>2.3 (-2.7;7.7)</td>
<td>0.36</td>
</tr>
<tr>
<td>Very low intensity activity, %</td>
<td>67.9 (9.7)</td>
<td>73.3 (9.0)</td>
<td>-5.3 (-11.0;0.4)</td>
<td>0.07</td>
</tr>
<tr>
<td>Low intensity activity, %</td>
<td>17.4 (5.7)</td>
<td>13.4 (5.7)</td>
<td>4.0 (0.5;7.5)</td>
<td>0.02</td>
</tr>
<tr>
<td>Moderate intensity activity, %</td>
<td>8.5 (3.9)</td>
<td>6.7 (2.7)</td>
<td>1.8 (-0.3;3.8)</td>
<td>0.08</td>
</tr>
<tr>
<td>High intensity activity, %</td>
<td>6.2 (2.7)</td>
<td>6.6 (2.1)</td>
<td>-0.4 (-1.9;1.0)</td>
<td>0.55</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear time, hours</td>
<td>14.2 (1.0)</td>
<td>14.8 (0.8)</td>
<td>-0.6 (-1.2;0.1)</td>
<td>0.02</td>
</tr>
<tr>
<td>Walking, hours</td>
<td>1.7 (0.5)</td>
<td>1.9 (0.4)</td>
<td>-0.2 (-0.5;0.04)</td>
<td>0.10</td>
</tr>
<tr>
<td>Standing, hours</td>
<td>3.1 (1.1)</td>
<td>3.4 (0.8)</td>
<td>-0.4 (-1.0;0.2)</td>
<td>0.21</td>
</tr>
<tr>
<td>Sedentary, hours</td>
<td>9.3 (1.4)</td>
<td>9.2 (1.2)</td>
<td>0.1 (-0.6;1.0)</td>
<td>0.66</td>
</tr>
<tr>
<td>Running, min</td>
<td>1.1 (1.6)</td>
<td>1.6 (2.9)</td>
<td>-0.5 (-1.9;0.9)</td>
<td>0.47</td>
</tr>
<tr>
<td>Cycling, min</td>
<td>7.2 (10.7)</td>
<td>18.1 (13.1)</td>
<td>-11.0 (-18.3;3.6)</td>
<td>0.004</td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Sit to stand transfers, n | 48 (12.9) | 53 (13.6) | -5 (-13;3) | 0.21    

Physical activity was measured for 2–7 days and presented as means. Abbreviations: CECS: chronic exertional compartment syndrome; F.I.T.T: frequency, intensity, time and type.

hours). Patients had worn the accelerometer for an average of 6.6 days, ranging from two to seven days, and controls had worn the accelerometer for an average of 6.6 days, ranging from five to seven days. During a day, comparable levels of walking, standing and being sedentary were observed in persons with CECS and controls, respectively. Controls spent 11.0 minutes (95% CI: 3.6;18.5) more cycling per day than patients with CECS (p=0.004). On average, the two groups performed the same amount of very low, moderate, and high intensity activity per day, but patients performed 4.0pp (95% CI: 0.5;7.5) more low intensity activity than controls (p=0.02). There were no significant differences between the groups in number of daily steps, walking cadence or number of sit to stand transfers (Table 3).

**PATIENT-REPORTED LEG PAIN**

The last obtained NRS and Borg values were significantly higher for patients than controls (p<0.001) (Table 2). There was no association between either peak or absolute change StO2 and patient-reported leg pain (Table 4).

**DISCUSSION**

No differences were found in maximal isometric plantar- or dorsiflexion muscle strength between patients with CECS and a group of sex- and age-matched asymptomatic controls. Baseline StO2 was lower for patients with CECS than controls, however no difference existed when they experienced pain or reached exhaustion, even though patients with CECS did this significantly earlier than controls. Overall, no differences were found in daily physical activities and StO2 was not associated with leg pain.

Patients with CECS did not have greater muscle strength in isometric ankle plantar- or dorsiflexion compared with controls. In addition, no differences were found between the CECS-affected leg and the contralateral leg. Birtles et al. also observed no difference between isometric dorsiflexion in patients with CECS and asymptomatic controls. However, they did report a significant difference in eccentric dorsiflexion, favouring patients with CECS. Further, Birtles et al. did not observe a difference in muscle thickness or change in muscle size after the exercise between patients and controls.

In the present study, patients with CECS had significant lower StO2 in the affected compartment before running on the treadmill compared to controls. However, the baseline group difference was no longer apparent at peak exercise StO2. This result contrasts with the study by van den Brand et al., who did not find a difference in baseline StO2 between 15 patients with CECS and eight healthy volunteers, but observed a significant group difference at peak exercise StO2. Moreover, patients with CECS had a lower peak exercise StO2 than the healthy volunteers and also lower change scores. The mean baseline StO2 was 87 (SD 11) for the 20 legs of patients with CECS and 91 (SD 5) for the 16 legs of the healthy volunteers in the study by van den Brand et al. In the current study, baseline StO2 was 64.3 (SD 5.4) among the 24 patients with CECS and 68.8 (SD 7.4) among the 24 controls. Baseline StO2 was thus very different between this study and the study by van den Brand et
Table 4. Associations between oxygen saturation and patient-reported leg pain in patients with chronic exertional compartment syndrome and controls.

<table>
<thead>
<tr>
<th></th>
<th>Patients with CECS</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Correlation&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Correlation between NRS and peak exercise StO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>24</td>
<td>-0.27</td>
</tr>
<tr>
<td>Correlation between NRS and absolute change StO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>24</td>
<td>0.16</td>
</tr>
<tr>
<td>Correlation between EILP-D and peak exercise StO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>23</td>
<td>0.05</td>
</tr>
<tr>
<td>Correlation between EILP-D and absolute change StO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>23</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<sup>a</sup>Spearman’s Rank Correlation. Abbreviations: CECS: chronic exertional compartment syndrome; NRS: Numeric Rating Scale; EILP-D: Exercise Induced Leg Pain Danish; StO<sub>2</sub>: oxygen saturation.

al., which is probably explained by differences in study population as the patients in the study by van den Brand et al. were all in the army and were predominantly young men. In addition, the difference could indicate a possible systematic difference between the two measurement systems as well as the testing procedures, as van den Brand et al. used two InSpectra™ Spectrometers (Hutchinson Technology Inc., Hutchinson, Minnesota) and tested both legs.

Patients with CECS did not spend more time walking and standing than controls and sedentary time was also similar between groups. In addition, there were no differences between the groups in the number of daily steps, walking cadence or number of sit to stand transfers. Controls, however, spent 11 minutes more cycling per day than patients with CECS. This could indicate that patients with CECS avoid cycling. This is interesting as cycling has been reported as both a conservative treatment in CECS as well as part of rehabilitation after fasciotomy. Furthermore, both patients and controls had a mean number of daily steps and walking cadence exceeding the minimum recommendations for physical activity (7000-8000 steps per day for healthy adults with a cadence of 100 steps per minute). The physical activity level among controls included in this study was generally comparable to the physical activity level in a group of asymptomatic controls included in a similar study of young individuals from the same geographical area, although different recruitment methods had been applied.

The physical activity level found among controls in the current study thus seems representative for young Danish individuals.

There was a statistically significant difference in running time during testing, as patients on average experienced pain or reached exhaustion 3.5 min. (95% CI: 1.7:5.3) earlier than controls. Despite this, there was no association between StO<sub>2</sub> and leg pain. The included patients with CECS experienced more exercise-induced leg pain than controls. Also, patients had statistically significant more lower leg pain when resting and during activity throughout the day than controls. Patient-reported pain of the lower leg was measured using EILP-D and VAS, both valid and reliable methods. Birles et al. used a Numeric Rating Scale (NRS) ranging from 0-10 to assess pain among patients with CECS and a group of asymptomatic controls, 24 and 48 hours after assessment. They also observed a statistically significant difference in pain levels between patients and asymptomatic controls during activities. Thus, pain is the primary parameter that distinguishes patients with CECS from controls.

**STRENGTHS AND LIMITATIONS**

A strength of this study is the relatively high number of patients and controls compared to similar studies in patients with CECS. The study by van den Brand et al. included 13 patients and eight healthy volunteers, while Birles et al. included 10 patients and 14 healthy controls. However, a sample size calculation was not performed, and the study population was thus based on a convenience sample. Moreover, the comprehensive test procedure, allowing investigation of both muscle strength, StO<sub>2</sub>, daily physical activity and patient-reported leg pain is a strength. A limitation to the NIRS measurement was that ultrasound was not used to evaluate the placement of the PortaMon above the painful...
compartment. The NIRS measurement may thus be biased by measurement errors.

CONCLUSION

The included patients with CECS did not differ from the asymptomatic controls in lower leg muscle strength, oxygen saturation, or physical activity. However, patients experienced higher levels of lower leg pain than controls during running, daily activities and at rest. There was no association between oxygen saturation and lower leg pain between groups.

ACKNOWLEDGEMENT

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CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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Original Research

Landing Technique and Ankle-dorsiflexion Range of Motion are not Associated with the History of Lower Limb Injuries among Youth Basketball Athletes

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**Background**

Lower limb injuries generate a significant health burden in basketball. Landing technique and ankle-dorsiflexion range of motion have been suggested as risk factors for lower limb injuries among youth athletes, but studies conducted specifically with basketball athletes are lacking.

**Hypothesis/Purpose**

To describe the period prevalence of basketball-related injuries and to examine the association of the history of lower limb injuries with landing technique and ankle-dorsiflexion range of motion asymmetry among youth basketball athletes.

**Study Design**

Cross-Sectional Survey.

**Methods**

Youth basketball athletes were asked to complete a paper-based survey to investigate personal characteristics, training characteristics and their three-month history of basketball-related injuries. The Landing Error Scoring System and the Weight-Bearing Lunge Test were used to evaluate landing technique and ankle-dorsiflexion range of motion. Binary logistic regression was utilized to examine the association of the investigated variables with the presence of history of lower limb injuries among the athletes.

**Results**

A total of 534 athletes participated. The three-month prevalence of basketball-related injuries was 23.2% (95% CI 19.7 – 27), and the majority of the reported injuries affected the lower limbs (69.7%; n=110). Sprains were the most frequent type of injury (29.1%; n=46), and the ankle (30.4%; n=48) and knee (21.5%; n=54) were the most affected anatomic locations. Landing technique (p = 0.105) and ankle-dorsiflexion range of motion asymmetry (p = 0.529) were not associated with the history of lower limb injuries.

**Conclusion**

The three-month prevalence of basketball-related injuries was 23.2%. Although ankle sprains were the most frequent injury, landing technique and ankle-dorsiflexion range of
motion asymmetry were not associated with the history of lower limb injuries among youth basketball athletes.

**Level of Evidence**

3

**INTRODUCTION**

Basketball is one of the most popular youth sports worldwide. In the United States, basketball is the most popular sport among boys and girls aged 12-17 years and, in Brazil, it represents the sixth most practiced team sport among Brazilians aged 15-19 years. As a physical activity, basketball provides a myriad of physical, mental and psychosocial health benefits to these age groups, but it also imposes a risk of sustaining an injury during participation. The incidence of basketball-related injuries (BRIs) varies depending on factors related to the investigated population – age, sex, level of participation – and the injury definition adopted by the study authors, but according to prospective cohort studies and a recent systematic review, the vast majority of BRIs affect the lower limbs.

The prevention of lower limb injuries has become a topic of great concern in basketball. The identification of modifiable risk factors is an important step for injury prevention. In basketball, two commonly reported risk factors for lower limb injuries are landing technique and ankle-dorsiflexion range of motion (ROM), and previous studies recommended the application of specific screening methods to evaluate these variables among basketball athletes. Two of those methods include the Landing Error Scoring System (LESS) and the Weight Bearing Lunge Test (WBLT), which have already proven their validity and reliability for evaluation of landing technique and ankle-dorsiflexion ROM, respectively.

Despite the use of these screening methods, the influence of landing technique and ankle-dorsiflexion ROM on injury risk is unclear. A previous case-control study conducted with high school and collegiate athletes of eight different varsity sports found no relationship between LESS score and the risk of sustaining an anterior cruciate ligament (ACL) injury, but a more recent prospective cohort study showed that a LESS score of < 5 significantly increased the risk of sustaining an ACL injury among elite-youth soccer athletes. Studies addressing the role of ankle-dorsiflexion ROM on injury risk also show inconclusive results. A prospective cohort study conducted specifically with youth basketball athletes showed an association between lower ankle-dorsiflexion ROM and the risk of developing patellar tendinopathy. Regarding lateral ankle sprains, a case-control study conducted with collegiate athletes found an association between greater ankle-dorsiflexion ROM and the risk of sustaining recurrent lateral ankle sprains, but a previous prospective cohort study conducted with army recruits showed that the occurrence of lateral ankle sprains was associated with a reduction in ankle-dorsiflexion ROM.

The sport and age of the investigated athletes are important reasons for these observed divergencies. To move the research forward, it is important to investigate these variables among athletes of different ages and sports. Considering the high lower limb injury rate in basketball, the purposes of this study were to describe the period prevalence of BRIs and to examine the association of the history of lower limb injuries with landing technique and ankle-dorsiflexion ROM asymmetry among youth basketball athletes.

**METHODS**

**STUDY DESIGN AND PARTICIPANTS**

This cross-sectional study was developed in association with a state basketball federation in Brazil. The state basketball federation aimed to enhance injury prevention efforts among youth athletes affiliated with the organization. The investigation of the history of BRIs and the evaluation of landing technique and ankle-dorsiflexion ROM by using two screening methods were proposed as a first step. The objectives were presented to the basketball teams during the 2018 pre-season conference and all youth basketball teams competing in the 2018 state basketball championship were invited to participate in the study. Training and match locations were visited by the researchers in previously scheduled days to recruit athletes to participate. Recruitment and data collection occurred between February and July 2018. Eligibility criteria included (1) youth athletes of both sexes, (2) aged between 10 and 19 years old. Professional athletes were not included in the study. Youth athletes who were not able to complete ankle-dorsiflexion ROM and/or landing technique evaluation due to any physical complaint were included in the study, but they participated only by completing the baseline questionnaire. All participants and their parents or legal guardians, for athletes younger than 18 years old, signed a consent or assent form prior to inclusion in the study. The study was approved by the Ethics Committee of the Universidade Federal de São Paulo (number 2880146).

**DATA COLLECTION**

Data collection was accomplished in two steps. First, athletes completed a paper-based questionnaire to investigate personal characteristics, training characteristics, and their history of BRIs in the prior three months. In the second step, athletes performed landing technique and ankle-dorsiflexion ROM evaluation in a random order. Data collection occurred after training sessions or official matches, providing a minimum period of ten minutes rest between the end of the activity and the beginning of the evaluations.
**BASELINE QUESTIONNAIRE**

The baseline questionnaire was completely self-reported and composed of open-ended and closed-ended questions. The initial version of the questionnaire was developed by the first author of the study and later discussed and validated by all the authors in a roundtable discussion. Variables related to personal characteristics (age, sex, height, weight), training characteristics (sport experience, sport specialization, frequency and duration of practice sessions) and history of BRIs in the prior three months were collected. The investigation of the history of BRIs was carried out through two open-ended questions about the type and the anatomical location of injuries. Subsequently, all self-reported injuries were categorized by two of the authors of the study based on the first two digits of the classification The Orchard Sports Injury Classification System (OS-ICS) Version 10.24 Any disagreement was solved by a third author of the study. The adopted injury definition during data collection was "any physical complaint sustained by a player that resulted from a basketball match or basketball training, irrespective of the need for medical attention or time loss from basketball activities".25

**LANDING TECHNIQUE EVALUATION**

The Landing Error Scoring System (LESS) was used to evaluate landing technique.17 All athletes received instructions and observed a test demonstration prior to the start of the assessment. Test procedures followed the description made by Padua et al.17 Athletes were positioned on a 30-cm-high box and instructed to jump horizontally towards a rectangular landing area – 100-cm-long, 50-cm-wide, and 1-cm-high – positioned at a distance of approximately 50% of their height in front of the box. Immediately after landing, they had to jump vertically as high as they were able and land again on the platform (Figure 1). Athletes completed at least three repetitions for familiarization with the jumping-landing task, which were followed by three valid trials. All valid trials were captured by two webcams (Logitech C920 Hd Pro Full Hd 1080p) placed at a distance of 3.5 m from the lens of the webcams to front of and to the side of the landing area. Both webcams were positioned on a tripod fixed at a height of 1.2 m from lens to floor. The webcams were connected to two independent notebooks and synchronized to the software provided by the manufacturer (Logitech Webcam Software, version 2.80.853.0a).

The jump was considered valid when the athlete (1) jumped from the box with both feet simultaneously, (2) jumped forward and did not perform an excessive vertical movement to reach the landing platform, (3) landed with the entire feet on the platform and (4) completed the task in a fluid motion.17

The authors did not provide any instruction to athletes regarding their landing technique during the test unless they were performing the test incorrectly. All examiners were physiotherapists who had participated in a previous two-hour training session, where they received theoretical and practical instruction about LESS.

**Figure 1. Landing Error Scoring System**

After data collection, in a second step, the videos were analyzed by three of the study authors, who were blinded to injury history. Intrarater and interrater reliability were estimated prior to the beginning of the analysis. For reliability analysis, the authors independently scored 24 jumping-landing task videos from eight different athletes at two time points, separated by one week. The intraclass correlation coefficients (ICC’s) were estimated based on a mean-rating, consistency, 2-way mixed-effects model. The ICC’s for intrarater and interrater reliability were 0.87 and 0.81, respectively.

The software Kinovea for motion analysis (version 0.8.15; Copyright 2006-2011 - Joan Charmant & Contrib.) was used during all the LESS analysis. The raters gave scores to each of the three valid attempts completed by each athlete and the final score was represented by the average value obtained in the three attempts. All LESS items were assessed bilaterally, and a preferred limb was not chosen for the analysis. The score for each item was awarded in cases where the athlete presented the landing error in at least one of the valid attempts made, regardless of whether the error was observed in only one or both lower limbs, in the cases of the items assessed bilaterally.

**ANKLE-DORSIFLEXION RANGE OF MOTION EVALUATION**

Weight-Bearing Lunge Test (WBLT), as described by previous authors, was used to evaluate the ankle-dorsiflexion ROM.18,21–23 A one-meter tape line was drawn on the floor and continued up to the wall for one more meter. Athletes were positioned with their heel and second toe aligned on the line. After positioning, the athlete was instructed to lunge forward to touch the vertical line in the wall with their knee, while maintaining foot alignment and heel contact with the floor. The evaluated foot was gradually moved away from the wall until the athlete was able to make only a slight contact with their knee on the vertical line. At that moment, ankle-dorsiflexion ROM was measured placing a smartphone 10 centimeters below the proximal region.
of the tibial tuberosity (Figure 2). The Ankle-dorsiflexion measurement was performed using the iHandy Level app (iHandy Ltd.), which is a valid and reliable tool for joint angle measurement.26 Lower limbs were randomly evaluated, and the final score was represented by the ankle-dorsiflexion ROM asymmetry observed.

All raters were physiotherapists who had participated in a previous two-hour face-to-face training where they received theoretical and practical instruction on the test. Raters were blinded to the presence of injury history during data collection. We did not conduct an intrarater and interrater reliability analysis of the measurements for ankle-dorsiflexion ROM before data collection.

STATISTICAL ANALYSIS

All youth basketball teams affiliated with the state basketball federation were invited to participate in this study and a convenience sample of youth athletes was utilized to describe the three-month prevalence of BRI, landing technique and ankle-dorsiflexion ROM asymmetry in this population.

Descriptive statistics were used to present the distribution of the investigated variables. Shapiro-Wilk test was used to verify the distribution of the data. An univariate analysis, using Independent Student’s t-test and Mann-Whitney test, was conducted to verify differences in LESS scores and ankle-dorsiflexion ROM asymmetry between athletes with and without history of lower limb injuries. Additionally, binary logistic regression was used in a multivariate analysis to investigate the association of the investigated variables with the presence of history of lower limb injuries among the athletes. Covariates and variables identified as associated factors in previous studies were used in the model. The model was adjusted considering multicollinearity and goodness-of-fit. The results were presented as odds ratios (OR) and 95% CI. For continuous variables the ORs indicate the change in odds for a one-unit increase in the independent variable. P-values less than 0.05 were considered statistically significant. The software Jamovi (version 1.6.21.0) was used for the analysis.

RESULTS

One hundred and forty-three male and female youth basketball teams belonging to 44 clubs participated in the 2018 state basketball championship. The state basketball championship categorizes youth by age to form the teams. Male competitions were played in seven categories: U-12 (17 teams), U-13 (20 teams), U-14 (17 teams), U-15 (17 teams), U-16 (16 teams), U-17 (13 teams) and U-19 (14 teams). Female competitions were played in five categories: U-15 (five teams), U-14 (four teams), U-15 (six teams), U-17 (nine teams) and U-19 (five teams).

In total, 540 athletes were recruited to participate in the study. After checking and confirming the eligibility criteria, 554 athletes belonging to 42 teams from 23 clubs were included in the final sample. Six athletes were not included because they were also members of the professional teams in their clubs.

All participants completed the baseline questionnaire. Landing technique and ankle-dorsiflexion ROM assessments were completed by 448 and 500 athletes, respectively. However, LESS results of 86 athletes were not included in the final analysis due to technical problems with the quality of the videos and/or execution errors identified during the analysis, which invalidated one or more jumps performed by the athlete.

CHARACTERISTICS

The majority of the participants were male (88.7%; n = 474). The median age of the athletes was 12 (IQR = 2) years old and 77.5% (n = 414) of them reported basketball as the only sport modality in which they participate. Detailed information about athletes’ characteristics is described in Table 1.

PREVALENCE OF BASKETBALL-RELATED INJURIES

The three-month prevalence of BRIs was 23.2% (95% CI 19.7 – 27), with 158 injuries sustained by 124 athletes. Sprains were the most frequent type of injury (29.1%; n = 46) (Table 2).

The ankle (30.4%; n = 48) and knee (21.5%; n = 34) were the most affected anatomic locations (Table 3). Lower limb injuries accounted for the majority of the reported musculoskeletal injuries (69.7%; n = 110) and the three-month prevalence of lower limb musculoskeletal injuries was 17.2% (95% CI 14.1 – 20.7).
Table 1. Athletes Characteristics. All continuous variables are expressed by the median and interquartile range. Categorical variables are expressed in percentage and total number of athletes.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total sample (n=534)</th>
<th>With history of lower limb injuries (n=86)</th>
<th>Without history of lower limb injuries (n=414)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>88.7 (474)</td>
<td>15.8 (75)</td>
<td>84.2 (399)</td>
</tr>
<tr>
<td>Female</td>
<td>11.3 (60)</td>
<td>28.4 (17)</td>
<td>71.6 (43)</td>
</tr>
<tr>
<td>Age (years)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12 (2)</td>
<td>12 (3.25)</td>
<td>12 (1.75)</td>
</tr>
<tr>
<td><strong>BMI (kg/m²)</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.1 (4.94)</td>
<td>21.3 (3.90)</td>
<td>19.8 (4.92)</td>
</tr>
<tr>
<td><strong>Sport experience (months)</strong></td>
<td>24 (24)</td>
<td>36 (30.3)</td>
<td>24 (24)</td>
</tr>
<tr>
<td><strong>Basketball exposure</strong>&lt;sup&gt;a&lt;/sup&gt; (hours/week)</td>
<td>7.5 (4)</td>
<td>8 (7.63)</td>
<td>7.5 (3)</td>
</tr>
<tr>
<td><strong>Category</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-12</td>
<td>39.5 (211)</td>
<td>11.8 (25)</td>
<td>88.2 (186)</td>
</tr>
<tr>
<td>U-13</td>
<td>43.4 (232)</td>
<td>14.2 (33)</td>
<td>85.8 (199)</td>
</tr>
<tr>
<td>U-14</td>
<td>4.7 (25)</td>
<td>20 (5)</td>
<td>80 (20)</td>
</tr>
<tr>
<td>U-15</td>
<td>4.7 (25)</td>
<td>44 (11)</td>
<td>56 (14)</td>
</tr>
<tr>
<td>U-17</td>
<td>4.4 (24)</td>
<td>41.6 (10)</td>
<td>58.4 (14)</td>
</tr>
<tr>
<td>U-19</td>
<td>3.2 (17)</td>
<td>47 (8)</td>
<td>53 (9)</td>
</tr>
<tr>
<td><strong>Sport specialization</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specialist</td>
<td>77.5 (414)</td>
<td>17.4 (72)</td>
<td>82.6 (342)</td>
</tr>
<tr>
<td>Generalist</td>
<td>22.5 (120)</td>
<td>16.7 (20)</td>
<td>83.3 (100)</td>
</tr>
</tbody>
</table>

BMI = body mass index,
<sup>a</sup> Continuous variables
<sup>b</sup> Categorical variables

Table 2. Type of Basketball-related Injuries

<table>
<thead>
<tr>
<th>Type of injury</th>
<th>% (n)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non specific injury</td>
<td>17.1 (27)</td>
</tr>
<tr>
<td>Bruising/haematoma</td>
<td>1.9 (3)</td>
</tr>
<tr>
<td>Laceration/abrasion</td>
<td>1.3 (2)</td>
</tr>
<tr>
<td>Whiplash</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Muscle injury</td>
<td>12.6 (20)</td>
</tr>
<tr>
<td>Tendon injury</td>
<td>10.1 (16)</td>
</tr>
<tr>
<td>Joint sprains</td>
<td>29.1 (46)</td>
</tr>
<tr>
<td>Cartilage injury</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Joint dislocations</td>
<td>7 (11)</td>
</tr>
<tr>
<td>Chronic instability</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Synovitis, impingement, bursitis</td>
<td>1.3 (2)</td>
</tr>
<tr>
<td>Fracture</td>
<td>12 (19)</td>
</tr>
<tr>
<td>Stress fracture</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Other stress/overuse injury</td>
<td>6.3 (10)</td>
</tr>
<tr>
<td>Organ injury</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Nerve injury</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Vascular injury</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Arthritis</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Other injury not elsewhere specified</td>
<td>1.3 (2)</td>
</tr>
</tbody>
</table>

<sup>a</sup> The type of basketball-related injuries are expressed in percentage and total number of injuries.

Table 3. Anatomic Location of Basketball-related Injuries

<table>
<thead>
<tr>
<th>Anatomic location</th>
<th>% (n)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>1.9 (3)</td>
</tr>
<tr>
<td>Neck</td>
<td>0.6 (1)</td>
</tr>
<tr>
<td>Shoulder</td>
<td>6.3 (10)</td>
</tr>
<tr>
<td>Upper arm</td>
<td>1.3 (2)</td>
</tr>
<tr>
<td>Elbow</td>
<td>0.6 (1)</td>
</tr>
<tr>
<td>Forearm</td>
<td>1.9 (3)</td>
</tr>
<tr>
<td>Wrist and hand</td>
<td>9.5 (15)</td>
</tr>
<tr>
<td>Chest</td>
<td>0.6 (1)</td>
</tr>
<tr>
<td>Trunk and abdomen</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Thoracic spine</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Lumbar spine</td>
<td>7 (11)</td>
</tr>
<tr>
<td>Pelvis and buttock</td>
<td>0.6 (1)</td>
</tr>
<tr>
<td>Hip and groin</td>
<td>1.3 (2)</td>
</tr>
<tr>
<td>Thigh</td>
<td>3.2 (5)</td>
</tr>
<tr>
<td>Knee</td>
<td>21.5 (34)</td>
</tr>
<tr>
<td>Lower leg</td>
<td>5.1 (8)</td>
</tr>
<tr>
<td>Ankle</td>
<td>30.4 (48)</td>
</tr>
<tr>
<td>Foot</td>
<td>7.6 (12)</td>
</tr>
<tr>
<td>Location unspecified</td>
<td>0.6 (1)</td>
</tr>
</tbody>
</table>

<sup>a</sup> The anatomic location of basketball-related injuries are expressed in percentage and total number of injuries.
Table 4. Landing Technique of the Athletes. LESS Score is expressed by the mean and standard deviation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total sample (n=362)</th>
<th>With history of lower limb injuries (n=57)</th>
<th>Without history of lower limb injuries (n=305)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LESS score</td>
<td>5.45 (± 2.34)</td>
<td>5.06 (± 2.41)</td>
<td>5.52 (± 2.32)</td>
<td>0.167</td>
</tr>
</tbody>
</table>

LESS = landing error system

Table 5. Ankle-dorsiflexion Range of Motion Asymmetry of the Athletes. ADROM asymmetry is expressed by the median and interquartile range.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total sample (n=500)</th>
<th>With history of lower limb injuries (n=86)</th>
<th>Without history of lower limb injuries (n=414)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADROM asymmetry</td>
<td>2.30 (2.70)</td>
<td>2.15 (2.60)</td>
<td>2.30 (2.70)</td>
<td>0.961</td>
</tr>
</tbody>
</table>

ADROM = ankle-dorsiflexion range of motion

LANDING TECHNIQUE AND ANKLE-DORSIFLEXION RANGE OF MOTION

The mean LESS score among the investigated athletes was 5.45 (± 2.34) points. There was no statistically significant difference between LESS scores in the groups with and without a three-month history of lower limb injuries (p = 0.167) (Table 4).

The median ankle-dorsiflexion ROM obtained was 37.2° (IQR 9.1°). There was no statistically significant difference between the ROM asymmetry values obtained by the groups with and without a three-month history of lower limb injuries (p = 0.961) (Table 5).

FACTORS ASSOCIATED WITH LOWER LIMB INJURIES

Table 6 describes the results of the multivariate analysis. Binomial logistic regression model showed that the category of the athlete was the only factor associated with the presence of a three-month history of lower limb injuries. LESS score (p = 0.105) and ankle-dorsiflexion ROM asymmetry (p = 0.529) were not associated with the presence of a three-month history of lower limb injuries.

DISCUSSION

The aims of this study were to describe the period prevalence of BRIs and to examine the association of lower limb injuries with landing technique and ankle-dorsiflexion ROM asymmetry among youth basketball athletes. The three-month prevalence of BRIs among the investigated athletes was 23.2% and the majority of the reported injuries affected the lower limbs. The ankle and knee were the most common anatomical locations affected by injuries and sprains were the most common type of injury. There was no association of landing technique and ankle-dorsiflexion ROM asymmetry with the history of lower limb injuries. Multivariate analysis showed that the category – meaning youth athletes were categorized by age for competition – was the only variable associated with the history of lower limb injuries.

Two previous studies conducted with youth basketball athletes found different period prevalence of BRIs, with values varying from 19.6% to 39%. The prevalence of BRIs may vary according to injury definition, seasonality of data collection, population characteristics and recall bias. Both previous studies adopted a ‘time loss’ injury definition and investigated one-year prevalence of BRIs among youth basketball athletes with a similar mean age, but the level of participation and the weekly basketball exposure of the athletes varied across the studies. According to the age category, some athletes tend to present a greater probability of suffering a BRI. Pappas et al. also found an increase in injury rates for the five most common basketball injuries presenting to emergency departments when comparing 7- to 11-year-old category to 12- to 17-year-old category. One possible explanation for this difference is an increase in total exposure and intensity of basketball activities and findings of the multivariate analysis may offer support for this hypothesis. Leppänen et al. investigated competitive athletes participating in basketball activities for 9-10 hours/week and Vanderlei et al. investigated boys and girls participating in a sport initiation program – with a low level of training and competitiveness – during 6-7 hours/week. A broader injury definition was adopted in this study to investigate the three-month prevalence of BRIs in a sample of competitive athletes, but the injury prevalence found was similar to that reported by Vanderlei et al. It may have occurred because the recall period was lower, and the majority of the participants were from categories of initiation in competitive basketball – U-12 and U-13 – and presented a low weekly basketball exposure. A three-month recall period was adopted to reduce the influence of recall bias that may have affected prevalence estimations, but on the other hand this choice increased the influence of the seasonality of data collection in the results. Data collection was conducted during the beginning of the 2018 regular season and the three-month recall period included off-season months. Regarding anatomical location and type of the reported injuries, the current findings are similar to those reported in a recent systematic review and two prospective cohort studies conducted with high school and collegiate athletes. These studies results indicated that the majority
of the BRIs affected the ankle and knee, and sprains were the most common type of injury.10–12

There was no association between landing technique and ankle-dorsiflexion ROM and the history of lower limb injuries. These associations are not well established in the literature. Smith et al. found no association between LESS scores and ACL injuries among high-school and collegiate athletes of eight different sport modalities, but Padua et al. showed that a LESS score > 5 was associated to an increased risk of sustaining an ACL injury specifically among elite-youth soccer athletes.19,20 In the present study only basketball athletes were investigated, and the outcome was not ACL injury. Mean LESS score for total sample was 5.34 and both groups – with and without history of lower limb injuries, had a mean LESS score > 5. Regarding ankle-dorsiflexion ROM, three previous studies identified an association between ankle-dorsiflexion ROM, measured using the WBLT, and lower limb injuries. Backman and Danielson prospectively investigated youth basketball athletes and showed that an ankle-dorsiflexion ROM < 36.5° was associated with an increased risk of developing patellar tendinopathy during the season.21 In a case-control study conducted with collegiate athletes of eight different modalities, Kobayashi et al. found that an ankle-dorsiflexion ROM > 49.5° were associated with an increased risk of suffering recurrent lateral ankle sprain, but, on the other hand, a large prospective cohort study conducted with army recruits showed that an ankle-dorsiflexion ROM < 34° was associated with a five-fold risk of suffering a lateral ankle sprain.22,23 Based on these results, it is unclear if restriction of or excess of ankle-dorsiflexion ROM are associated with the occurrence of lower limb injuries. All three previous studies used the absolute ankle-dorsiflexion ROM value as the outcome. In the present study, ankle-dorsiflexion ROM asymmetry was adopted. Mean ankle-dorsiflexion ROM asymmetry for total sample was 2.50 and there was no difference when comparing the group with and without history of lower limb injuries. Absolute ankle-dorsiflexion ROM may be a more relevant variable to be further investigated. Age, sex, sport, and the injury defined as the outcome are potential factors that could influence this association.19,20 This study investigated only basketball athletes and participants were younger than the athletes investigated in these three previous studies. The majority of them were beginning in competitive basketball with a low weekly basketball exposure. Additionally, the outcome was lower limb injuries in general and not restricted to ACL injuries, patellar tendinopathy, or lateral ankle sprains. LESS and WBLT were proposed and previously investigated as screening tools for specific lower limb injuries, but the statistical power did not enable the consideration of these specific injuries as the outcomes in the current analysis.15,16 Statistical power was cited as a limitation by the authors of a previous study, and they raised the need for multicenter initiatives to better elucidate these associations.19

This study described the prevalence of BRI’s and investigated landing technique and ankle-dorsiflexion ROM among a large sample of youth athletes from a specific sport. Regardless of these strengths, the study has some limitations. First, a cross-sectional study is not the ideal study design to measure injury rates and describe injury patterns due to the seasonality of data collection. Additionally, the associations found in a cross-sectional study are subjected to reverse causation and cannot establish causal relationships between the investigated variables and the occurrence of lower limb injuries. Second, a broader injury definition was adopted, all BRIs were self-reported and, due to recall bias, athletes were more prone to report substantial injuries and to potentially forget minor complaints. For ankle-dorsiflexion ROM evaluation, although previous face-to-face training on data collection procedures was conducted, it was not possible to conduct a reliability analysis of the raters because data collection occurred in different locations and had a different set of raters in each

### Table 6. Binary Logistic Regression Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution % (n)</th>
<th>OR (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>16 (58)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>84 (304)</td>
<td>1.26 (0.52-3.03)</td>
<td>0.599</td>
</tr>
<tr>
<td>BMI (Kg/cm²)</td>
<td></td>
<td>0.97 (0.89-1.07)</td>
<td>0.641</td>
</tr>
<tr>
<td>Category</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-12</td>
<td>51 (185)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>U-13</td>
<td>25.7 (93)</td>
<td>1.82 (0.79-4.15)</td>
<td>0.155</td>
</tr>
<tr>
<td>U-14</td>
<td>7 (25)</td>
<td>3.04 (0.92-10.03)</td>
<td>0.067</td>
</tr>
<tr>
<td>U-15</td>
<td>6.1 (22)</td>
<td>7.66 (2.50-23.48)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>U-17</td>
<td>6.3 (23)</td>
<td>7.64 (2.55-22.88)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>U-19</td>
<td>3.9 (14)</td>
<td>10.34 (2.47-43.13)</td>
<td>0.001</td>
</tr>
<tr>
<td>LESS score</td>
<td></td>
<td>0.89 (0.77-1.02)</td>
<td>0.105</td>
</tr>
<tr>
<td>ADROM asymmetry</td>
<td></td>
<td>0.95 (0.83-1.10)</td>
<td>0.529</td>
</tr>
</tbody>
</table>

OR = odds ratio, CI = confidence interval, BMI = body mass index, ADROM = ankle-dorsiflexion range of motion, LESS = landing error scoring system. Predictive Measures of the model: accuracy (0.83), specificity (0.96), sensitivity (0.05) Nagelkerke’s R² = 0.143
location. Ankle-dorsiflexion ROM asymmetry was used as the outcome because the laterality of the injuries was not collected. Previous studies adopted the absolute ROM of the affected limb as the outcome of the analysis which may affect the association.21–23 Lastly, although broader inclusion criteria were established, the majority of the sample was composed by male athletes from U-12 and U-13 basketball teams. All male U-12 basketball teams and 75% of the male U-13 basketball teams affiliated with the State Basketball Federation were investigated, but difficulties recruiting female and older male athletes reduced the external validity of the current findings.

Establishing the epidemiology and modifiable risk factors for injuries are essential to inform the development and the implementation of injury prevention interventions among different groups of athletes.13,14 These results may influence future studies including prospective investigations to bring more solid data about the epidemiology of BRIs among youth basketball athletes and to better elucidate the role of landing technique and ankle-dorsiflexion ROM as risk factors for lower limb injuries in this population. For clinical practice, although the current prevalence data is insufficient, in the absence of large prospective cohort studies, these results may be useful for clinicians to direct their injury prevention efforts for the most common BRIs observed among youth basketball athletes. Finally, clinicians should be cautious to infer the injury risk of youth basketball athletes solely based on the results of screening tests, such as LESS and WBLT. Screening tests may be applied, but we need to consider the multicausality of sports-related injuries and the predictive capacity of these tests when interpreting their results.

CONCLUSION

The three-month BRIs prevalence among youth basketball athletes was 23.2%. Although ankle sprains were the most frequent injury, landing technique and ankle-dorsiflexion ROM asymmetry were not associated with the history of lower limb injuries. The age category of the athlete was the only variable associated with the history of lower limb injuries.

COMPETING INTERESTS

The authors declare that they have no competing interests in the subject matter or materials discussed in this manuscript.

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Original Research

The Falcon Test: An Observer Agreement Study in Subjects With and Without Anterior Knee Pain

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Keywords: Rectus femoris muscle, muscle length test, Ely's test, reliability

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Introduction

A shortened rectus femoris muscle has been associated with many different musculoskeletal problems. Assessing rectus femoris muscle length is commonly performed using the Modified Thomas Test. However, this test position is often difficult to assume and there are difficulties with reliably measuring rectus femoris length. A method that that uses an easier position to assume and could be more reliable would be beneficial to therapists. The purpose of this study was to determine observer agreement using a new test for assessment of rectus femoris length. A second purpose was to determine if those with anterior knee pain have different rectus femoris muscle length than those without anterior knee pain.

Method

Fifty-three participants with and without anterior knee pain were enrolled. Rectus femoris muscle length was measured lying prone with the leg measured on the table while the non-measured leg was off the table in a position of 90° hip flexion. Rectus femoris muscle was lengthened by passively bending the knee until a firm end-feel. The angle of knee flexion was then measured. The process was then repeated after a brief rest period.

Results

Observer agreement assessing rectus femoris length using this method showed "almost perfect" reliability for both intra- and inter-rater testing: intra-rater: ICC = .99, [CI95: .98-.99], inter-rater: ICC = .96, [CI95: .92-.98]. Agreement for the sub-sample of those with anterior knee pain (N=16) showed "almost perfect" reliability for intra-rater (ICC 1,1 = .98); [CI95: 0.94-.99] and inter-rater reliability (ICC 2,1 = 0.88); [CI95: 0.70 -.95]. No differences were noted in rectus femoris length between those without and those with anterior knee pain (t= 0.82, p> 0.01); [CI95: -7.8 -3.33]; (SEM = 1.5°; MDC=3.6°).

Conclusion

This new method of assessing rectus femoris length is reliable between and within raters. No differences were noted in rectus femoris length between those with anterior knee pain and those without.

INTRODUCTION

Assessing the length of the rectus femoris muscle is a standard part of a lower extremity examination for physical therapists. The rectus femoris is the only two-joint muscle of the quadriceps group, and like many of the other lower extremity two-joint muscles, it can lose muscle length. A shortened rectus femoris muscle is associated with a number of different lower extremity problems including adolescent apophysitis of the tibial tubercle (Osgood-Schlatter's
disease),1–7 rectus femoris muscle strain,8–10 calcific tendinosis of the rectus femoris muscle,11 osteoarthritis of the knee,12–14 as well as anterior knee pain.15–17 Thus, an assessment of rectus femoris length is an important part of a physical therapy examination.

The most commonly described method used to assess rectus femoris muscle length is the Thomas test.18 Only a few researchers have examined the reliability of the Thomas test to assess the length of the rectus femoris muscle. Eng et al. reported "almost perfect" reliability (ICC = 0.94) test-retest reliability for quadriceps femoris muscle angle, but they failed to describe their method of how they measured quadriceps femoris angle or to report what kind of reliability tests were performed, either intra or inter-rater observer agreement.19 Horneij et al. assessed rectus femoris muscle length on 44 nurses or aides with and without back pain using a modified Thomas test, however they only rated rectus femoris muscle length using a nominal measurement scale as either "tight" or "excessive" muscle length.20 In another study, Harvey et al. assessed the length of all of the thigh two-joint muscles, however, the flexibility data was pooled so there is no way to determine observer agreement of any of the specific muscle tests.21 Peeler and Anderson, in an observer agreement study examining the Modified Thomas Test, assessed rectus femoris length measures taken by three athletic trainers and found moderate to fair test-retest intra-rater (ICC = 0.67) and inter-rater (ICC = 0.50) reliability.22 The "moderate" reliability findings may, in part, be due to the difficulty in properly performing the Modified Thomas test. Peeler and Anderson report that the Thomas test can be challenging for clinicians to perform.22 Cady et al assessed rectus femoris length using the Thomas test in 20 healthy men using digital photographs, among six raters, but they did not record goniometric measures and only used a nominal rating of pass or fail.23 Thus, from one suitable study, the reliability of the Modified Thomas test to assess rectus femoris muscle length, was "high" for inter-rater reliability with a Chronbach's alpha of 0.80.23 A drawback in this study was that used nominal data, which increased their likelihood of agreement.

A current method that is easier for patients to assume and for therapists to perform, that does not stress the lower back or hips is Ely's test. Ely's test, used to assess rectus femoris muscle length, is a method that does not include holding the contralateral hip in full flexion, thus making it easier to perform. Peeler and Anderson assessed Ely's test for inter and intra-rater reliability using measurements taken by three athletic trainers on 54 participants with no history of trauma.24 Their results showed moderate reliability with ICC values of 0.69 for intra-rater reliability and 0.66 for inter-rater reliability.24 However, they only used active, not passive knee flexion, when assessing rectus femoris muscle.24 Oliencia et al. also assessed rectus femoris muscle length using Ely's test and found good inter-rater reliability (ICC = .90) and good intra-rater reliability (ICC = 0.91).25 But, they also only used active knee flexion to assess rectus femoris muscle length.25 According to Kendall muscle length testing is performed using passive not active movement that increases the distance from the origin and insertion which elongates the muscle in the opposite direction of the muscles action.18 Additionally, a muscle crossing two-joints like the hamstrings, are incapable of shortening sufficiently to produce complete range of knee flexion with the hip extended.18 Thus, the "true" or actual amount of rectus femoris muscle length, and thus the reliability which was recorded in these studies, using Ely's test is questionable.

Another method similar to Ely's test was previously described in the literature by Witvrouw et al.26 Witvrouw et al assessed rectus femoris muscle length in athletes with anterior knee pain.26 They described a method where the athlete assumes a prone position placing the contralateral (not measured) hip in a position of 90° of hip flexion to stabilize the pelvis and then flexing the ipsilateral (measured) knee assessing rectus femoris length.26 This position of assessing rectus femoris muscle length is often easier for patients to assume and easier for therapists to perform the test. An advantage of this test method over Ely's is that it allows for better pelvic stabilization by preventing unwanted pelvic movement. The new test examined in this study mimics the Thomas test position to some extent by flexing the contralateral hip when lying prone. It may also be desirable in those who are very flexible. When using Ely's test with flexible patients, full knee flexion can be halted because the heel reaches the buttocks and prevents any further knee flexion. This new test rarely has that problem and can often discriminate left to right rectus femoris muscle length imbalances in flexible patients.

The purpose of this study was to determine observer agreement using a new test for assessment of rectus femoris length. A second purpose was to determine if those with anterior knee pain have different rectus femoris muscle length than those without anterior knee pain.

The authors hypothesized that this new method of assessing rectus femoris muscle length is reliable, and that those with anterior knee pain will demonstrate shorter rectus femoris muscle length than those who do not have anterior knee pain.

METHODS

PARTICIPANT

Fourteen men and thirty-nine women (N = 53) participated in this study after volunteering through convenience sampling from Maryville University and the surrounding community looking for subjects with and without anterior knee pain. Anterior knee pain was defined as pain in an around the patella without having recent injury or surgery and whose pain level was below 5/10 on a numeric pain rating scale. Demographic data were gathered on all participants. Participants were included if they were between 18 to 65 years of age and could tolerate lying prone for at least 15 minutes. Exclusion criteria: if they could not speak or understand the English language, were mentally disabled, had undergone previous surgery on one or both knees, had recent injury or trauma to either knee within the prior six months (where their knee was assessed by a licensed health
care provider), needed an assistive device for gait, had a history of structural problems of the ligaments of either knee (such as sprains due to any causative factor), or were pregnant. The study was approved by the IRB committee at Maryville University in St. Louis, MO.

A flip of a coin was used to determine which side to measure the left (heads) or right (tails) side, to avoid the issue of “double-dipping” the data. All participants completed a Lower Extremity Functional Scale (LEFS). A Numeric Pain Rating Scale (NPRS) was used to assess current, worst, and best pain. A high-low treatment table was used for participants to lie on while measurements were taken. A standard 12-inch plastic goniometer was used to measure hip flexion of 90° while in prone position prior to data collection.

Participants reviewed and signed an informed consent form and were assigned a random participation number used throughout data collection. Eligibility to participate in the study was verified with an inclusion and exclusion, yes or no, questionnaire. The participants’ demographic information was gathered, and the participants were asked to fill out two self-reported measures. The first measure was related to functional ability using the LEFS. Then participants’ pain level was assessed for present anterior knee pain they were having at this time and for their worst pain level perceived in the prior six months on a 0 to 10 NPRS, with 0 = no pain and 10 at its worst. If both knees met inclusion and exclusion criterion, or if both knees had pain, a coin was flipped to determine which knee, left or right, would be measured.

Rectus femoris muscle length (in the new measurement being studied) was measured using a new test, called the Falcon test, with the participants lying prone on a treatment table with the leg to be measured on the table while the other leg was placed off the side of the treatment table into a position of 90° of hip flexion with the foot placed on the ground (Figure 1) and the participant was told to maintain this position throughout the measuring process. One therapist measured the length of rectus femoris muscle by slowly passively bending the knee until a firm end-feel was first perceived. Another therapist, on the opposite side, measured the angle of passive knee flexion using a standard 12-inch plastic goniometer. (Figure 2) This process was completed three times, and the measurements were recorded by the measuring therapist. The mean of the three measurements were then used in statistical analysis.

After approximately five minutes of rest time, the process was repeated using the same methods and measurements were taken by another rater. The second-rater therapist was blinded to all of the goniometric recordings made by the first rater.

DATA ANALYSIS

Data analysis was performed using R, a Language and environment for statistical computing. Descriptive statistics, including means, standard deviations, skewness, and kurtosis of age, BMI, LEFS scores, and NPRS scores (now, best, and worst pain score), were calculated using R. Intraclass Correlation Coefficients (ICC) were calculated for inter- and intra-rater reliability of assessing rectus femoris length with the Falcon test using R for the entire sample (those with and without anterior knee pain) and also for just the sample with anterior knee pain. A shortened rectus femoris was examined to determine if this was related to those with anterior knee pain using the student’s t-test and also calculated the SEM and Minimal Detectable Change (MDC) using MDC = 2 * 1.41 * SEM for rectus femoris muscle length using the reliability data.
Table 1. Demographic Descriptive Statistics

<table>
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<tr>
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<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
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<tbody>
<tr>
<td>Age (yr)</td>
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<td>18</td>
<td>53</td>
<td>22.7</td>
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<tr>
<td>Height (cm)</td>
<td>36.8</td>
<td>153.7</td>
<td>190.5</td>
<td>164.2</td>
<td>13.6</td>
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<tr>
<td>Weight (kg)</td>
<td>67.7</td>
<td>50.5</td>
<td>115.4</td>
<td>71.6</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>15.6</td>
<td>16.4</td>
<td>32.1</td>
<td>24.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 2. Outcome Measures Descriptive Statistics

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<tr>
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<th>N</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
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<tr>
<td>Worst Pain (NPRS)</td>
<td>53</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>1.0</td>
<td>1.66</td>
</tr>
<tr>
<td>LEFS</td>
<td>53</td>
<td>20</td>
<td>60</td>
<td>80</td>
<td>78.9</td>
<td>3.25</td>
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<tr>
<td>Rectus Femoris Length (degrees)</td>
<td>53</td>
<td>58.00</td>
<td>100.50</td>
<td>158.50</td>
<td>134.53</td>
<td>10.13</td>
</tr>
</tbody>
</table>

RESULTS

Age, height, and weight of participants are described in Table 1.

The mean amount of maximum knee flexion (e.g., rectus femoris muscle length) for the Falcon test was 154° (Table 2); knee flexion motion ranged between 100 to 158°.

Observer agreement of assessing rectus femoris length for the full sample (N=55) using the Falcon test to assess rectus femoris length showed “almost perfect” reliability for both intra and inter-rater testing: intra-rater reliability ICC = .99, [CI95]: .98-.99 and inter-rater reliability; inter ICC = .96, [CI95]: .92-.98.

Observer agreement for the sub-sample of only those with anterior knee pain (N=16) showed “almost perfect” reliability for intra-rater reliability (ICC 1,1 = .98); [CI95]: 0.94-.99 and for inter-rater reliability (ICC 2,1 = 0.88); [CI95]: 0.70-.95. The SEM = 1.3°; MDC=3.6°.

There was no statistically significant difference between measurements in those without and with anterior knee pain (t= 0.82, p = 0.41); [CI95]: -7.8 -3.35.

DISCUSSION

Observer agreement using this new prone position rectus femoris length test named the Falcon test was found to be “almost perfect” with ICC’s above .95 for both inter- and intra-tester reliability. This method may improve upon the Modified Thomas test because with this position, having one leg off the treatment table, effectively stabilizes the pelvis without extra stabilization methods. Thus, unlike the Modified Thomas test, the therapist does not have to be concerned about maintaining the contralateral hip in full flexion to keep the lumbar spine flat on the treatment table. Also, this test position was much easier to assume, maintain, and get up from for all of the participants in this study. From experience using this test, this is also true for the patients with low back pain and hip pain, who often have considerable difficulty and pain trying to assume the Thomas test position.

The commonly used Modified Thomas test is not always easily performed. As many therapists know from experience, the sequencing of the many tasks involved with setting up a patient for the Modified Thomas Test can be difficult and often limit the ability of obtaining an accurate measurement of rectus femoris muscle length. For example, when flexing the ipsilateral knee, it is often difficult to prevent the contralateral hip from coming out of its fully flexed, knee to chest, position because of shortened hip flexor muscles. While trying to maintain the position of both hips and the ipsilateral knee, therapist then must measure the degree of knee flexion, while at the same time trying to maintain both hips positioning above the treatment table. Thus, in the clinic, for an accurate goniometric reading this test usually requires two therapists, one to stabilize and control unwanted pelvis or hip motion and the other to measure knee range of motion. Added to that, if the patient has more than a mild amount of pain, this can be very difficult for patients to assume as well as hold this position long enough to be measured. In a busy clinic this test is often difficult to accomplish.

This new test position is termed the Falcon test owing to its somewhat “bird” like pose of the patient when assuming this position, which needed a simple name so that therapist can easily describe to other colleagues the test position they used when assessing rectus femoris muscle length, rather than just calling the test the “prone, contralateral hip flexion to 90°, Ely’s test for rectus femoris muscle length”. The Falcon test may prove to be a better test than the Thomas test and Ely’s test because the pelvis can be stabilized better by flexing the contralateral hip to 90° and having the participant place their foot on the floor for stabilization. Placing the hip in full flexion, stabilizes the pelvis, preventing an unwanted increase in lumbar lordosis as well as any pelvic tilting, thus resulting in more reliable rectus femoris muscle length measurements. Thus, the Falcon test is just a Modified Thomas test turned “upside down”.

Using an Ely’s test to assess rectus femoris muscle length in some patients may be adequate for assessing rectus femoris muscle length. However, a common problem en-
countered with the Ely’s test is that when flexing the knee is that an end feel may not be achieved because range is limited by the heel contacting the buttock, creating a “ceiling effect”. This problem is found more often in females and in those with generalized hypermobility. A study by Sweeney et al. found that only six out of 67 female gymnast had rectus femoris limitation where they were not able to touch their heel to their buttocks with Ely’s test. Thus, although rectus femoris muscle length would not be considered short, the tests cannot distinguish if a muscle length difference may exist between the left and right sides. Side to side differences in rectus femoris muscle length do occur in patients, including patients after total knee arthroplasty, those with osteoarthritis of the patella and knee, patients with low back pain, and in athletes who sustain a rectus femoris muscle strain or injury. The Falcon tests allows a quick, easy assessment of rectus femoris muscle length in those with hypermobility, and after surgery or injury.

When comparing those with anterior knee pain to those without anterior knee pain there was not a significant difference in rectus femoris length between groups. However, this study was underpowered, likely by of those with anterior knee pain. Also, only one person in the group with anterior knee pain currently had considerable knee pain (6/10 NPRS) and the mean for the “worst pain” for the anterior knee pain group was only 2/10 on a NPRS while the mean current pain was 1/10. Thus, this sample may not have been representative of most who have anterior knee pain. Witvrouw et al. in a study of 430 athletes, showed that athletes with anterior knee pain had reduced rectus femoris muscle length when compared to those without anterior knee pain (124.6 versus 132.2 degrees). The inclusion criteria in the current study only included those with a 5/10 anterior knee pain or lower. Because the aim of the current study was to determine the intra and inter-tester reliability of the Falcon Test, patients with reported knee pain above 5/10 were not included to ensure that knee pain did not interfere with achieving an end range on the test, indicating a false positive for short rectus femoris muscle length.

LIMITATIONS

Although there were 53 participants in this study, most of the participants were female (N=39), also the average population age was younger (mean age = 22.7 years). Only 16 of the participants reported a history of anterior knee pain and of those must had only minor anterior knee pain (1/10). A limitation of the Falcon test as studied herein is that two therapists were used to assess rectus femoris muscle length, one to assess muscle end feel and maintain end range knee flexion, the other to measure the degree of knee flexion. Extreme care was taken to make sure that the second therapist did not observe the other therapist when measuring knee flexion. In hindsight, using a bubble goniometer or an electric goniometer would have eliminated the need for two therapists to measure rectus femoris muscle length. However, the position, not the measuring device, was the main focus in this study. A minor limitation to the Falcon test is that larger or pregnant patients may have difficulty lying prone.

CONCLUSIONS

A new test, named the Falcon test, showed “almost perfect” reliability for both intra and inter-rater agreement, indicating that this test can be used repeatedly in clinical practice. The MDC for the Falcon test was found to be 3.6 degrees. No difference in rectus femoris muscle length measurements were found between those with anterior knee pain and those without anterior knee pain, however, the sample size was small.

CONFLICTS OF INTEREST

The authors report no conflicts of interests.

Submitted: April 19, 2022 CDT, Accepted: January 15, 2023 CDT
REFERENCES


Background
Well-developed physical qualities (i.e., greater load capacity) in athletes can provide protection against injuries. Although higher competitive level swimmers have more developed physical qualities, no studies have investigated how physical qualities of the shoulder respond to a swim-training session in different competitive levels.

Purpose
To compare baseline shoulder external rotation range of motion (ER ROM) and isometric peak torque of the shoulder internal rotators (IR) and external rotators (ER) between national and university level swimmers with differing training volumes. To compare the post-swim changes of these physical qualities between groups.

Study design
Cross-sectional.

Methods
Ten male swimmers (age = 18.7 ± 1.2 years) were divided into high-load (N= 5 national-level, weekly swim-volume = 37.0 ± 2.7 km) and low-load groups (N= 5 university-level, weekly swim-volume = 6.8 ± 1.8 km). For each group, shoulder active ER ROM and isometric peak torque of the shoulder IR and ER were measured before and immediately after a high-intensity swim-training session (for each group, the hardest swim-session of the week was analyzed). The results were evaluated by the level of significance (p-value), effect size, and whether changes exceeded the measurement error.

Results
University-level swimmers had lower baseline ER torque (p= 0.006; d= 2.55) and IR torque (p= 0.011; d= 2.42) than national-level swimmers. For post-swim analysis, ER ROM decreased more in university swimmers (change = -6.3° to -8.4°; d= 0.75-1.05) than national counterparts (change = -1.9° to -5.7°; d= 0.43-0.95). Greater drops in rotation torque were found in university swimmers (IR change = -15% to -21.0%; d= 0.83-1.66; ER change = -9.0% to -17.0%; d= 1.14-1.28) compared to national swimmers (IR change = -10.0% to -13.0%; d= 0.61-0.91; ER change = -5.7% to -9.1%; d= 0.50-0.96). The average change of all tests in university swimmers exceeded the minimal detectable change (MDC), whereas in national level swimmers some tests exceeded the MDC. Despite this, only post-swim ER torque in the dominant side (p= 0.005; d= 1.18) was significantly lower in university swimmers (possibly due to the small sample size).
Conclusions

University swimmers have less baseline shoulder external and internal rotator torque and had greater drops of all shoulder physical qualities after a swim-training session, which may have implications for injury risk. However, due to the sample size, the results have to be interpreted with caution.

Level of evidence

INTRODUCTION

The shoulder is the most commonly injured body part in swimmers with a prevalence reported as high as 91%. Level of competition has been reported as a potential nonmodifiable risk factor for shoulder pain in this population. This might be explained as swimmers of a higher competitive level are exposed to greater chronic loads (e.g. weekly swim-training volume and number of training sessions). However, higher levels of competition have been also associated with more developed physical qualities such as aerobic capacity and shoulder strength, which might be also protective against injury in swimmers (‘training load-injury paradox’). Feijen et al. found that club-level swimmers had a higher risk of shoulder pain than regional-level counterparts during a two-year follow-up. A possible explanation for this is that fitter and stronger athletes (i.e., higher load capacity) can better tolerate the amount of and changes in workloads.

Some authors have investigated how swimmers respond to training loads. These researchers found that a swim-training session negatively affects shoulder physical qualities such as rotation strength, rotation ROM, pectoralis minor length, and joint position sense. Since some of these physical qualities have been considered potential risk factors for shoulder pain in swimmers, their acute impairments can increase the risk of shoulder injury. The injury-etiolo model proposed by Windt & Gabbett suggests that the risk of injury can increase as a result of training loads applied and the negative effects on modifiable risk factors (e.g., physical qualities). Although these studies investigated different levels of competition, it is difficult to make comparisons as the swim-sessions studied varied in terms of volume, intensity, and time. Therefore, it is unknown whether higher-level swimmers (i.e., stronger and fitter athletes) have less significant decreases in physical qualities than lower-level counterparts after a similar training session.

To date, some authors have shown that swimmers of a higher competitive level have more developed shoulder physical qualities. However, no studies have compared the postswim changes in shoulder physical qualities between different levels of competition. Investigating this can help to understand whether higher chronic loads and well-developed physical qualities affect post-training shoulder responses. This might have implications in the prevention of shoulder pain in specific groups. The primary aim of this study was to compare the baseline differences in shoulder ER ROM and isometric peak torque of the shoulder internal and external rotators between university and national level swimmers with differing training volumes. A secondary aim was to compare the postswim changes of these physical qualities between groups. It was hypothesized university swimmers would have less developed physical qualities at baseline. Also, that these physical qualities would be more affected after the training session in university swimmers.

MATERIALS AND METHODS

PARTICIPANTS

A sample of ten male participants was included in the study. Participants were divided into two groups according to their level of competition: high-load (university level; N = 5) and low-load (national level; N = 5). Participants of both groups were matched by gender, age, and years of swim experience, but differed in training volume. All swimmers trained within the same group during the year, completed the same practices regularly, and participated in either university or national championships. The exclusion criteria included a history of shoulder surgery, shoulder pain at the time of the study, and any pain in the two weeks prior to study that interfered with the ability to train or compete fully. All participants provided written informed consent. This study was approved by the university’s ethics board and conducted in accordance with the Declaration of Helsinki (Ref.no.HSR1718-100).

PROCEDURES

The same researcher (MY) performed all the tests in both groups. For each swimmer, measurements were recorded before and after a swim-training session. On the testing day, general demographic information of participants, such as sex, age, limb dominance, height, mass, and forearm length, were recorded. Before the procedure testing, participants performed a standardized land-based warm-up consisting of shoulder movements. Immediately after the warm-up, baseline measurements were recorded in the following order: shoulder ER ROM, and isometric peak torque of the shoulder internal and external rotators. All the tests were standardized, and the dominant arm was assessed first. Three subsequent testing trials of each test were performed in both limbs, and the results were averaged for further analysis. Immediately after completion of the training, swimmers exited the pool and repeated baseline testing.

INSTRUMENTATION AND OUTCOME MEASURES

Regarding shoulder-rotation ROM, only ER was measured. The reason for this was because previous authors have
found changes in ER ROM, but not in internal rotation (IR) after a swim-session. Shoulder ER ROM was measured using the 'Goniometer Pro' (Siu5 Co, 159 Bloomfield, NJ) digital inclinometer application for the iPhone (Apple, Inc, Cupertino, CA), which is valid compared to the universal goniometer.\textsuperscript{16} Participants were positioned in supine with the shoulder in 90° of abduction and were instructed to actively rotate the limb back until the available end range.\textsuperscript{17} A towel roll was placed under the humerus to ensure correct alignment in the frontal plane. This was based on visual inspection, making sure that the humerus was levelled to the acromion process. The end range was determined by the available range without any stabilization.\textsuperscript{17}

Isometric peak torque of the shoulder internal and external rotators was measured using a hand-held dynamometer (Hoggan MicroFET2; 166 Scientific LLC, Salt Lake City, UT), which is reliable and valid compared to the gold standard isokinetic dynamometry.\textsuperscript{18} Participants were positioned in supine with the shoulder in 90° of abduction. Before testing, one submaximal trial was performed to ensure correct technique. The HHD was placed on the palmar surface of the forearm for IR and on the dorsal aspect of the forearm for ER, proximal to the radioulnar joint crease. Then, participants were instructed to push against the HHD as hard as possible for three seconds, with a resting period of 10 seconds. Then, two further trials were performed. Force was converted into torque (newton meters) by multiplying the force (in newtons) by the lever arm length (meters) of the dominant and nondominant sides. Next, torque was normalized to body mass (Nm/kg) and expressed as the percentage of change between measurements. To assess muscle balance, the ratio between external and internal rotator isometric peak torque was calculated (ER: IR ratio).

Intrarater test-retest reliability for shoulder ER ROM and rotation torque was established before in a pilot study. Each measurement was taken before and after a two-hour period (average duration of a swim-training session). The intraclass correlation coefficient, standard error of measurement (SEM), and minimal detectable change (MDC) with 95% of confidence interval for each test were calculated (Table 1).

<table>
<thead>
<tr>
<th>Test</th>
<th>Side</th>
<th>Intraclass Correlation Coefficient (3,3)&lt;sup&gt;a&lt;/sup&gt; (95% CI)</th>
<th>Standard Error of Measurement&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Standard Error of Measurement&lt;sup&gt;d&lt;/sup&gt; (%)</th>
<th>Minimal Detectable Change&lt;sup&gt;c&lt;/sup&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External rotation range of motion, a</td>
<td>Dominant</td>
<td>0.980 (0.922-0.995)</td>
<td>2.39</td>
<td>2.30</td>
<td>6.61</td>
</tr>
<tr>
<td></td>
<td>Nondominant</td>
<td>0.990 (0.919-0.998)</td>
<td>1.70</td>
<td>1.66</td>
<td>4.72</td>
</tr>
<tr>
<td>External rotation torque, Nm/kg</td>
<td>Dominant</td>
<td>0.992 (0.905-0.998)</td>
<td>0.02</td>
<td>4.47</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Nondominant</td>
<td>0.999 (0.994-1.000)</td>
<td>0.01</td>
<td>2.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Internal rotation torque, Nm/kg</td>
<td>Dominant</td>
<td>0.982 (0.925-0.996)</td>
<td>0.03</td>
<td>6.34</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Nondominant</td>
<td>0.997 (0.990-0.999)</td>
<td>0.01</td>
<td>2.62</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Table 1. Two-Hour Test-Retest Reliability for the Outcome Measures Calculated from the Pilot Study (N = 10)**

Abbreviations: CI, confidence interval.
\( ^a \) Two-way mixed model. A coefficient > 0.90 is considered excellent reliability, <0.89 to > 0.80, good, <0.79 to > 0.70, moderate, and < 0.70, low.
\( ^b \) Standard deviation \( x \) \( \sqrt{1 - \text{intraclass correlation coefficient.} \) \( ^c \) Calculated as standard error of measurement \( x \) 1.96 x \( \sqrt{2} \).
\( ^d \) Standard error of measurement and minimal detectable change % were calculated by dividing their respective value with the average of the test and retest values.

**DESCRIPTION OF THE TRAINING SESSIONS**

For each group, the hardest swim-session of the week was analyzed. The rationale for this was because studies have found changes in shoulder physical qualities after a high-intensity swim-training but not after a moderate to low training session.\textsuperscript{12,13} Based on the coach’s perception, the Wednesday evening session was chosen. Both groups data were collected on the same day of the week, time, and period of the year. Both sessions lasted one hour. The only difference between sessions was the total swim-volume performed; national level swimmers performed a greater volume (3 km) than university swimmers (2 km). To assess how swimmers perceived the intensity of the training, the session-RPE (sRPE) was calculated. sRPE is a valid and reliable method to monitor training load in various sports and populations.\textsuperscript{19} Two methods of sRPE were used to quantify the internal training load: sRPE\textsuperscript{h} and sRPE\textsuperscript{km}.\textsuperscript{20}

First, the intensity of the session was quantified by the RPE based on the modified version of the category-ratio scale of Borg.\textsuperscript{21} Immediately after completing the training, the swimmers were asked, "how hard was your workout", using an 11-point scale with 0 corresponding to ‘rest’ and 10 to ‘maximal’ effort. For sRPE\textsuperscript{h}, the RPE score was multiplied by the session duration (min) and expressed in arbitrary units (AU). Whereas, for sRPE\textsuperscript{km}, the RPE was multiplied by the volume (km) and also expressed in arbitrary units (AU). This method has been used especially in swimmers to quantify internal training loads as includes the volume swam.\textsuperscript{20,22} Collette et al.\textsuperscript{20} found that the sRPE\textsuperscript{km} was the strongest measure associated with the recovery-stress status of swimmers during a training season.

**STATISTICAL ANALYSIS**

For statistical analysis, SPSS version 25 for Windows (Inc, Chicago, IL) was used. Demographic data were initially screened for between-group differences using independent sample t-tests for normally distributed data and Mann Whitney test for non-normally distributed data. For postswim changes, results were expressed as means and
Table 2. Descriptive characteristics of participants

<table>
<thead>
<tr>
<th></th>
<th>University swimmers (n = 5)</th>
<th>National swimmers (n = 5)</th>
<th>Between group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range (min-max)</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Age (y)</td>
<td>19.4 ± 0.9</td>
<td>20.0 (19 – 21)</td>
<td>18.0 ± 1.2</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>83.2 ± 5.2</td>
<td>140.0 (75.0 – 89.0)</td>
<td>69.9 ± 6.9</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.0 ± 12.3</td>
<td>30.0 (155.0 – 185.0)</td>
<td>171.8 ± 10.5</td>
</tr>
<tr>
<td>Weekly swim-volume (km)</td>
<td>6.8 ± 1.8</td>
<td>4.0 (6.0 – 10.0)</td>
<td>37.0 ± 2.7</td>
</tr>
<tr>
<td>Weekly training sessions (n)</td>
<td>2.6 ± 0.9</td>
<td>2.0 (2-4)</td>
<td>8.2 ± 1.1</td>
</tr>
<tr>
<td>Weekly training hours (hr)</td>
<td>5.2 ± 1.8</td>
<td>4.0 (4-8)</td>
<td>16.8 ± 1.1</td>
</tr>
<tr>
<td>Swimming experience (y)</td>
<td>8.8 ± 1.6</td>
<td>3.0 (7.0 – 10.0)</td>
<td>8.0 ± 0.84</td>
</tr>
<tr>
<td>History of shoulder pain (yes: no)</td>
<td>4:1</td>
<td>4:1</td>
<td>1:0</td>
</tr>
</tbody>
</table>

<sup>a</sup> Significant difference between groups (p < 0.05).

standard deviation (SD) as all data presented a normal distribution (Shapiro-Wilk's test). Paired student t-test was used to assess within-group differences between pre- and post-measurements and independent sample t-tests were used to assess between-group differences. Differences were considered as significant when p values were < 0.05. Also, Cohen’s d effect size (ES) was calculated to determine the magnitude of any difference between measurements. The following ES values were considered: > 0.8 (large), between 0.5 and 0.79 (medium), between 0.49 and 0.20 (small), and < 0.2 (trivial). Finally, whether the results exceeded or not the measurement error (MDC) was also used to analyze differences. Given the small sample size (n = 10), results were presented in scatterplots to examine data distribution.

RESULTS

No differences were found between groups for age, sex, height, years of swim, and history of shoulder pain (Table 2). The high-level group reporter greater swim-training volume (p < 0.001), hours of training (p < 0.001), training sessions (p < 0.001), and less body mass (p = 0.009) than the low-level group.

BASELINE DIFFERENCES BETWEEN GROUPS

Table 3 shows baseline differences of the outcome measures. University swimmers presented a lower baseline torque than national counterparts for external rotators (dominant side: p = .007; d = 2.50 and nondominant side: p = 0.006; d = 2.55) and internal rotators (dominant side: p = 0.011; d = 2.12 and nondominant side: p = 0.014; d = 2.42). There was no significant difference between groups for ER ROM and ER: IR ratio. Individual analysis showed that 80% and 100% of national swimmers had higher baseline rotator torque than university counterparts in dominant and nondominant side, respectively.

POST-SWIM SHOULDER EXTERNAL ROTATION ROM

Table 4 shows pre-post differences of the outcome measures. Figure 1 presents the results for shoulder ER ROM. University swimmers reported mean decrease in ER ROM with moderate ES for the dominant side (p = 0.005; change = -8.4°; d = 0.74). Although decreases in the nondominant side had large ES (d = 1.05; change = -6.4°), the difference was not significant (p = .062). The mean value of change on both sides exceeded the MDC. Individual analysis showed that all participants in this group reduced the ER ROM on both sides. Furthermore, 80% of the participants exceeded the MDC in the dominant side and 40% in the nondominant side.

In national swimmers, no significant pre-post differences were found on either side. Despite this, the ES was large for the dominant side (d = 0.95) and moderate for the nondominant side (d = 0.45). The mean value of change on the dominant side only exceeded the SEM, whereas, on the nondominant side, did not exceed the measurement error. Individual analysis showed that all participants reduced ER ROM on the dominant side and 80% on the nondominant side. Furthermore, 20% of the participants exceeded the MDC on both sides. There was no significant difference between groups.

POST SWIM SHOULDER ROTATION ISOMETRIC TORQUE

Figure 2 presents the results for shoulder rotator peak torque and shoulder ER:IR ratio. Regarding internal rotator torque, university swimmers reported a significant mean decrease with large ES for the dominant side (p = 0.024; change = 21.5%; d = 1.66). Although the decreases in the nondominant side had large ES (change = 15.1%; d = 0.83) the difference was not significant (p = 0.108). On both sides, the mean value of change exceeded the MDC. Individual analysis showed torque reductions in all participants in the dominant side and 80% in the nondominant side. Furthermore, 60% of the participants exceeded the MDC values in both sides. National swimmers had significant decreases with large ES for the dominant side (p = 0.002; change = 13.9%; d = 0.91) and moderate ES for the nondominant side (p = 0.001; change = 10.7%; d = 0.61). The mean value of change exceeded the MDC in the nondominant side and only the SEM in the dominant side. Individual analysis showed torque reductions in all participants in both sides. Furthermore, 20% of the participants exceeded the MDC in the dominant side and 80% in the nondominant side.

For external rotator torque, university swimmers reported a significant mean decrease with large ES for the
Table 3. Baseline difference between groups for shoulder external rotation range of motion and rotation isometric peak torque normalized to body weight.

<table>
<thead>
<tr>
<th>Test</th>
<th>University swimmers</th>
<th>National swimmers</th>
<th>Mean difference</th>
<th>p Value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Rotation ROM, °</td>
<td>105.3 ± 10.9</td>
<td>100.3 ± 3.3</td>
<td>5.00</td>
<td>0.376</td>
<td>0.70</td>
</tr>
<tr>
<td>MDC</td>
<td>97.4 ± 5.6</td>
<td>98.2 ± 4.0</td>
<td>0.80</td>
<td>0.973</td>
<td>0.17</td>
</tr>
<tr>
<td>External rotator torque, Nm/kg</td>
<td>0.43 ± 0.05</td>
<td>0.53 ± 0.03</td>
<td>0.10</td>
<td>0.007⁴</td>
<td>2.50</td>
</tr>
<tr>
<td>MDC</td>
<td>0.39 ± 0.05</td>
<td>0.53 ± 0.06</td>
<td>0.14</td>
<td>0.006⁴</td>
<td>2.55</td>
</tr>
<tr>
<td>Internal rotator torque, Nm/kg</td>
<td>0.41 ± 0.08</td>
<td>0.59 ± 0.09</td>
<td>0.18</td>
<td>0.011⁴</td>
<td>2.12</td>
</tr>
<tr>
<td>MDC</td>
<td>0.40 ± 0.06</td>
<td>0.63 ± 0.13</td>
<td>0.24</td>
<td>0.014⁴</td>
<td>2.42</td>
</tr>
<tr>
<td>ER: IR ratio</td>
<td>1.08 ± 0.11</td>
<td>0.92 ± 0.14</td>
<td>0.16</td>
<td>0.081</td>
<td>1.28</td>
</tr>
<tr>
<td>MDC</td>
<td>0.97 ± 0.12</td>
<td>0.85 ± 0.12</td>
<td>0.12</td>
<td>0.167</td>
<td>1.00</td>
</tr>
</tbody>
</table>

D = dominant shoulder, ND = non-dominant shoulder. ⁴ Significant difference between groups (p < 0.05).

Figure 1. Scatterplots showing preswim and postswim changes in shoulder ER ROM for university and national swimmers.
A, dominant shoulder. B, nondominant shoulder. The bold lines indicate the mean value.

don dominant side (p = 0.004; change = 17.2%; d = 1.28). Although reductions in the nondominant side had large ES (change = 9.0%; d = 1.14), the difference was not significant (p = 0.075). On both sides, the mean value exceeded the MDC. Individual analysis showed torque reductions in all participants in the dominant side and 80% on the nondominant side. Furthermore, 80% of the participants exceeded the MDC in the dominant side and 60% on the nondominant side. National swimmers had no significant differences in the dominant (p = 0.103; change = 3.7%; d = 0.50) and nondominant sides (p = 0.145; change = 9.1%; d = 0.96). On the dominant side, the mean value of change did not exceed the measurement error, and on the nondominant side, it exceeded the MDC. Individual analysis showed torque reductions in 80% of the participants on both sides. Furthermore, none of the participants exceeded the MDC in the dominant side and 60% in the nondominant side.

There was no significant difference between groups for internal rotator torque (both sides) and for nondominant side external rotator torque. However, external rotator torque of the dominant side was significantly lower in university swimmers compared to national counterparts (p = 0.003; d = 1.18).

SHOULDER ER: IR RATIO
University swimmers reported no significant differences between sides. Individual analysis showed increases in 80% of the participants in the dominant side and 60% in the nondominant. National swimmers reported a significant increase in the dominant side with large ES (p = 0.004; d = 0.80) but no differences in the nondominant side (p = 0.311). Individual analysis showed ratio increases in all participants in the dominant side and 80% in the nondominant.
Table 4. Mean Results from Preswim and Postswim of High-Intensity Training Sessions for Rotation Range of Motion and Isometric Peak Torque Normalized to Body Weight.

<table>
<thead>
<tr>
<th>Test</th>
<th>Side</th>
<th>Preswim</th>
<th>Postswim</th>
<th>Mean difference</th>
<th>Mean % change</th>
<th>Within group</th>
<th>Between groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>p-value</td>
<td>Effect size</td>
</tr>
<tr>
<td>University swimmers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External rotation ROM, °</td>
<td>D</td>
<td>105.3 ± 10.9</td>
<td>96.9 ± 11.9</td>
<td>-8.4</td>
<td>-8.1 ± 3.0</td>
<td>0.003&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>97.4 ± 5.6</td>
<td>91.1 ± 6.3</td>
<td>-6.3</td>
<td>-6.4 ± 5.5</td>
<td>0.062</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External rotator torque, Nm/kg</td>
<td>D</td>
<td>0.43 ± 0.05</td>
<td>0.36 ± 0.04</td>
<td>-0.07</td>
<td>-17.2 ± 6.0</td>
<td>0.004&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>0.39 ± 0.05</td>
<td>0.35 ± 0.04</td>
<td>-0.04</td>
<td>-9.0 ± 8.8</td>
<td>0.075</td>
<td>1.14</td>
</tr>
<tr>
<td>Internal rotator torque, Nm/kg</td>
<td>D</td>
<td>0.41 ± 0.08</td>
<td>0.32 ± 0.06</td>
<td>-0.09</td>
<td>-21.5 ± 9.4</td>
<td>0.024&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>0.40 ± 0.06</td>
<td>0.35 ± 0.03</td>
<td>-0.05</td>
<td>-15.1 ± 18.1</td>
<td>0.108</td>
<td>0.83</td>
</tr>
<tr>
<td>ER: IR ratio</td>
<td>D</td>
<td>1.08 ± 0.11</td>
<td>1.14 ± 0.11</td>
<td>+0.06</td>
<td>+6.3 ± 10.8</td>
<td>0.273</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>0.97 ± 0.12</td>
<td>0.99 ± 0.06</td>
<td>+0.03</td>
<td>+3.9 ± 11.3</td>
<td>0.600</td>
<td>0.12</td>
</tr>
<tr>
<td>National swimmers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External rotation ROM, °</td>
<td>D</td>
<td>100.3 ± 3.3</td>
<td>94.6 ± 4.5</td>
<td>-5.7</td>
<td>-5.7 ± 6.9</td>
<td>.127</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>98.2 ± 4.0</td>
<td>96.4 ± 4.5</td>
<td>-1.8</td>
<td>-1.9 ± 4.6</td>
<td>.421</td>
<td>0.43</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External rotator torque, Nm/kg</td>
<td>D</td>
<td>0.53 ± 0.03</td>
<td>0.51 ± 0.05</td>
<td>-0.02</td>
<td>-3.7 ± 4.0</td>
<td>.103</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>0.53 ± 0.06</td>
<td>0.48 ± 0.06</td>
<td>-0.05</td>
<td>-9.1 ± 9.6</td>
<td>.145</td>
<td>0.96</td>
</tr>
<tr>
<td>Internal rotator torque, Nm/kg</td>
<td>D</td>
<td>0.59 ± 0.09</td>
<td>0.51 ± 0.09</td>
<td>-0.08</td>
<td>-13.9 ± 4.0</td>
<td>.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>0.63 ± 0.13</td>
<td>0.55 ± 0.14</td>
<td>-0.08</td>
<td>-10.7 ± 5.1</td>
<td>.001&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.61</td>
</tr>
<tr>
<td>ER: IR ratio</td>
<td>D</td>
<td>0.92 ± 0.14</td>
<td>1.03 ± 0.13</td>
<td>+0.11</td>
<td>+12.0 ± 5.2</td>
<td>.004&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>ND</td>
<td>0.85 ± 0.12</td>
<td>0.90 ± 0.15</td>
<td>+0.05</td>
<td>+6.2 ± 11.9</td>
<td>.311</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Abbreviation: NA, not applicable, D=dominant, ND=non dominant
<sup>a</sup> Significant difference within group (p < 0.05).
<sup>b</sup> Significant difference between groups (p < 0.05).
SESSION–RPE

University swimmers reported an RPE average of 6.4 ± 1.5 (min-max = 5–9), whereas national counterparts an average of 8.2 ± 1.1 (min-max = 7–9). Considering that both groups performed a 60 minute session, sRPE\textsuperscript{h} average was 384 ± 91 AU (min-max = 300 – 540 AU) for university swimmers and 492 ± 65.7 AU (min-max = 420 – 540 AU) for national counterparts. The difference between groups was not significant (p = 0.064). Individual analysis showed that 80% of national swimmers reported higher RPE and sRPE\textsuperscript{h} than university. Regarding sRPE\textsuperscript{km}, university swimmers reported an average of 12.8 ± 5.0 AU (min-max = 10 – 18 AU) and national swimmers an average of 24.6 ± 3.5 AU (min-max = 21–27 AU). In this case, the difference was significant with large ES (p < 0.001; d = 3.75). Furthermore, all national swimmers reported higher sRPE\textsuperscript{km} than university counterparts.

DISCUSSION

The current study explored the relationship between training loads, physical qualities of the shoulder, and competitive level in swimmers. Due to the small sample size, the results were analyzed by the level of significance (p-value), magnitude of the difference (ES) and whether changes exceeded or not the measurement error (MDC). For the primary objective, the hypothesis was partially rejected. University swimmers had significantly less shoulder rotator torque at baseline. However, there was no baseline difference in shoulder ER ROM between groups. For the secondary objective, the hypothesis was also partially rejected. University swimmers experienced greater drops than national counterparts after a high-intensity swim-session. Despite this, only external rotator torque of the dominant side was significantly lower in university swimmers. The lack of significant differences in some variables might be explained by the small sample size. If groups are compared using ES and whether the results exceed the measurement error or not, university swimmers showed more meaningful decreases in all the physical qualities after the training session. This is important as the ES and MDC are less affected by the sample size.\textsuperscript{24}

These results suggest that higher chronic loads and well-developed physical qualities (i.e., greater baseline rotator torque) seem to be a protective factor of postswim drops in shoulder physical qualities. Furthermore, that lower-level swimmers (i.e., lower load capacity) are possibly at higher risk of shoulder injury after swim-training than their higher-level counterparts. Since shoulder ER ROM and rotation isometric peak torque are potential risk factors for development of shoulder pain in swimmers,\textsuperscript{2,14} their monitoring before and after a training session, especially in lower-level swimmers, might have implications for injury risk. However, the results must be interpreted with caution due to the small sample size.

GROUP CHARACTERISTICS

Both groups were composed of male swimmers of a similar age and years of swimming experience. The main differences between groups were the amount of training they had been exposed to. As competitive level increases, so does the number of sessions and swim-training volume.\textsuperscript{3} In our study, national swimmers performed on average 37.0 ± 2.7 km per week, which is 5.4 times more than the university swimmers (average = 6.8 ± 1.8 km). Furthermore, national swimmers performed an average of 11.6 hours and 5.6 sessions of extra training per week compared to university counterparts. This shows that national swimmers were exposed to higher chronic loads.

SHOULDER ROTATION TORQUE

Baseline rotation torque was significantly higher in national swimmers than university counterparts with large effect sizes (d = 2.12 to 2.55). All national swimmers were stronger than university swimmers in the dominant side and 80% were in nondominant side. This is supported by Bae et al.\textsuperscript{4} who found that international swimmers had greater shoulder rotator force measured by isokinetic dynamometry than national swimmers. A later study\textsuperscript{5} reported that elite swimmers had also greater strength in the shoulder extensors, flexors, abductors, and adductors muscles than recreational counterparts measured by a handheld dynameter. The current results are in accordance with these studies showing that swimmers of a higher competitive level have greater baseline shoulder force, which might be explained by the greater chronic loads they are exposed to. This is important as greater upper body strength has been associated with swimming performance.\textsuperscript{25–27} Furthermore, athletes with lower shoulder ER strength have higher shoulder injury rates after an increase of training loads,\textsuperscript{9} which might have implication for injury risk.

For postswim changes, internal rotation torque was significantly decreased in both groups, particularly in the dominant arm. Despite this, university swimmers reported greater mean decreases as a percentage of body weight (15% to 21%) than national swimmers (10% to 15%). Furthermore, they had more clinically meaningful drops (large ES and values exceeding MDC) than national counterparts (moderate to large ES and only the nondominant side exceeding MDC). Importantly, a higher percentage of university swimmers had drops exceeding the MDC. Despite this, there was no significant difference between groups, which might be explained by the small sample size. Shoulder internal rotator muscles are constantly activated during the pull-through phase of the stroke\textsuperscript{28} which can lead to muscle fatigue after a high-intensity swim-session.\textsuperscript{12} Two cross-sectional studies have found that internal rotator force deficits in swimmers with shoulder pain.\textsuperscript{29,30} However, due to the cross-sectional design, of these studies, it is unclear whether the decreases in internal rotator force is the cause or consequence of shoulder pain.

External rotation torque was also decreased in both groups. Although none of the groups reported significant decreases in the nondominant side, the percentage of
Figure 2. Scatterplots showing preswim and postswim scores in shoulder rotation torque for national and university swimmers.

change (9.0% and 9.1%), large ES, and swimmers exceeding the MDC value (60%) was similar between groups. The main difference was seen on the dominant side. Reductions in university swimmers (17% of body weight) were significant, with large ES, and with 80% of participants exceeding the MDC. On the contrary, national swimmers reported non-significant drops (3.7% of body weight) with small ES and none of the swimmers exceeding the MDC. These results support why external rotation torque in the dominant side was the only variable significantly different between groups \((p = 0.003; d = 1.18)\). Although shoulder external rotator muscles are less activated during swimming, their role is to control internal rotator forces.28 Labriola et al.31 have indicated that decreased infraspinatus activity can lead to glenohumeral instability, which may result in functional impingement. A recent study showed acute decreases of shoulder external rotator torque after a high-intensity swim-session.12 Interestingly, deficits in shoulder external rotator endurance rather than peak force have been reported as a potential risk factor for shoulder pain in swimmers in a cross-sectional52 and two prospective studies.7,33 Considering this, the authors recommend that future research explore postswim changes in shoulder external rotator endurance in this population.

Both groups increased their ER:IR ratio after a high-intensity swim-session, mainly in the dominant side. This means that proportionally, internal rotator torque was more affected than external rotator after a single training. Interestingly, national swimmers had greater increases in this ratio (6.2% to 12%) than university counterparts (3.9% to 6.3%). However, only the changes in the dominant side of national swimmers were significant. Contrary to the result of this study, Batalha et al.15 found no changes in shoulder ER:IR ratio after a swim-training session in competitive swimmers. This might be explained as the intensity of the session in the present study was high, whereas in Batalha et al.15 study was medium to low. Several authors have also investigated the changes in this ratio over a longer period,34–36 reporting reductions between 4% to 14% during a training period in young competitive swimmers. This shows that internal rotator torque increases proportionately more than external rotator during a training season.35 Therefore, while a training season decreases the ER:IR ratio, a single swim-session increases it. However, it remains unclear whether this imbalance (increase or decrease) is related to shoulder injuries. Two cross-sectional studies have found no relationship between the ER:IR ratio and shoulder pain32,57 and one prospective study found a relationship58 in competitive swimmers. This prospective study found that low preseason shoulder ER:IR ratio was associated to an increase risk of injury during a season.

In summary, the results of this study showed that a high-intensity swim-session decreased shoulder rotator torque and increased the ER:IR ratio in both groups. However, university-level swimmers reported more meaningful changes. Lower-level swimmers have less tolerance to maintain loads during a high-intensity swim-session, which result in greater fatigue of shoulder rotator muscles. Possibly, lower competitive level swimmers might be at higher risk of shoulder injury after a high-intensity swim-session.

SHOULDER ER ROM

Baseline shoulder ER ROM was similar between groups. Although one university swimmer presented more range in his dominant side, this was not consistent (Figure 1). To the authors knowledge, this is the first study to investigate baseline differences of shoulder ER ROM between levels of competition in swimmers. One study found that elite swimmers had more shoulder ER ROM (average of 15°) compared to a non-swimmer group.39 The greater ROM found in swimmers was explained by the repetitive shoulder elevation during the stroke.39 Although in the current study national swimmers were exposed to greater chronic loads (i.e., more repetitive shoulder elevation), the results showed no baseline difference between groups. This probably indicates that higher chronic loads in swimmers are more related to baseline differences in shoulder rotation force than ER ROM.

Regarding postswim changes, both groups reduced their shoulder ER ROM, predominantly in the dominant arm. However, the average decrease in university swimmers was greater (6.3° to 8.4°) and more meaningful (large ES and values exceeding MDC) than national counterparts (1.9° to 5.7° with small to large ES and values exceeding the SEM only). Despite this, the only changes in the dominant arm of university swimmers were significant. Individually, almost all swimmers reduced their ROM after the training session in both groups. Only one national swimmer increased the ROM in the nondominant side (Figure 1), which might explain the less significant result in this group. Interestingly, university swimmers presented a higher proportion of swimmers exceeding the MDC (40 to 80%) than national counterparts (20%). Despite this, the difference between groups was not significant. The results showed that, after a high-intensity swim-session, shoulder ER ROM decreased in both groups with more meaningful changes in low-level swimmers. Similarly, studies have also found reductions of ER ROM as a result of a single swim session10–12 and the accumulation of loads during a week.40 Importantly, deficits in shoulder ER ROM is a risk factor for shoulder pain in competitive swimmers.41 Since shoulder ER ROM is necessary during the mid-recovery phase when the arm is abducted at 90°, limitations of this movement may increase the probability of mechanical shoulder impingement.41

The findings are consistent with previous studies reporting decreases in shoulder ER ROM after a swim-training session in elite10 and national level swimmers.11,12 Interestingly, the study assessing the highest level of competition (i.e. elite) found the lowest drops in ER ROM (average = 3.4°),10 while the highest drops were found in the university group of the present study (average = 8.4° in the dominant side). This supports these results and suggests that higher competitive levels have less postswim reductions of shoulder ER ROM. However, it is difficult to make comparisons as the sessions are different in terms of intensity and distance. More studies with bigger sample sizes comparing
the effect of the same session in different groups might be necessary to confirm the current findings.

INTENSITY OF TRAINING SESSIONS

Despite national swimmers reporting less postswim changes in shoulder physical qualities, this group perceived the training session as harder. Both groups performed a one-hour session, but the national swimmers completed more volume (3 km) than university counterparts (2 km). To illustrate this, in the same period, national swimmers performed 33% more volume, which implies a higher intensity of the session and probably less recovery time throughout the session. This was expected as higher levels of competition perform greater swim-volumes and intensities. However, both training sessions were the hardest of the week which is proportional to the level of competition.

Comparing the sRPE^3, national swimmers perceived the session slightly harder, however, the differences between groups were not significant (p = 0.064; d = 1.35). Yet, if the sRPE^km is compared, national swimmers perceived the session harder with significant differences and larger ES (p < 0.000; d = 3.75). The difference obtained between the two methods might be explained because sRPE^km considers the volume instead of time. This shows that, in this study, sRPE^km was more appropriate than sRPE^3 to compare internal training loads between groups. This is supported by Collette et al.,30 who recommended the use of sRPE^km to monitor internal training loads as the influence of volume on the perceived exertion is greater than the training time in swimmers. Another explanation for the higher RPE found in national swimmers is the accumulation of training loads over the week. Although both groups were assessed the same day (Wednesday evening), at the testing day national swimmers had already performed five training sessions that week (average = 8.2 training sessions/week). Furthermore, they had done a morning session on the same day, while the university swimmers had only performed one or two sessions before the Wednesday session (average = 2.6 training sessions/week) and did not have a morning training on the testing day.

LIMITATIONS

This study presents limitations. First, although the study reported some findings (e.g., level of competition presenting more developed physical qualities and less postswim changes), it is underpowered (type II error). To be confident of the post-swim changes and differences between groups the study would have needed at least 16 participants per group (version 3.1.9.2; G*Power). Because of the small sample size, the value of the analysis was increased in several ways.42 An homogeneous sample investigated a: males between 17 and 20 years old with similar swimming experience. Although this can decrease the between-subject variability and increase the power of the study, the results cannot be generalized to other populations. Repeated measures of the dependent variables (shoulder physical qualities) were also performed to decrease the variability and increase the number of measurements. Finally, reliable tools were used to measure the participants. Unreliable tools can increase variability and affect outcomes.42 Another limitation might be the structure of the swim-session. Although the swim-sessions were the hardest for each group, there might have been some differences in terms of structure which could have influenced the results. Further research should investigate a larger sample size including other levels of competition and development of physical qualities (e.g., elite group). Also, understanding whether postswim changes of shoulder physical qualities are related to the development of shoulder pain might be necessary.

CONCLUSIONS

University level swimmers have lower baseline shoulder rotator torque than their national level counterparts, which might be explained by the lower chronic loads they are exposed to. This might, to some extent, explain the greater postswim drops of shoulder physical qualities in this group. However, due to the small sample size, the results have to be interpreted with caution. The current results might have practical implications for recreational swimmers and triathletes (lower chronic loads). Since higher baseline shoulder rotator torque and chronic loads seem to be a protective factor of postswim drops in shoulder physical qualities, lower-level swimmers (i.e., lower load capacity) may be at higher risk of shoulder injury after swim-training than higher-level swimmers (more trained, thus greater load capacity). A shoulder strengthening program and monitoring of shoulder physical characteristics before and after a training session might be beneficial for lower-level swimmers. However, it is unknown whether the postswim impairments on shoulder force and ROM are associated with shoulder injury in this population.

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Effects of Repetitive Pitching on Trunk Muscle Endurance and Thoracic and Shoulder Kinematics

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Keywords: baseball, kinematics, shoulder, torso, muscles

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Background
Baseball players are aware of the potential of shoulder problems due to repetitive throwing. However, few studies have examined how pitching repeatedly affects the thoracic spine and shoulder.

Purpose
This study aimed to determine the effects of pitching repeatedly on the endurance of trunk muscles and kinematics of the thoracic spine and shoulder.

Study design
Cohort study

Methods
Trunk muscle endurance was assessed in flexion, extension, and lateral flexion positions in 12 healthy amateur baseball players. The positions of stride foot contact (SFC) during the early cocking phase and maximal shoulder external rotation (MER) during the late cocking phase were used to compute the thoracic and shoulder kinematics in degrees. Participants were then asked to throw 135 fastballs (~9 innings with 15 throws per inning). Throwing motions were monitored throughout the first, seventh, eighth, and ninth innings, whereas trunk muscular endurance was assessed before and after the repetitive throwing activity. Ball speed during pitching was measured using a radar gun. All outcome measures were statistically compared to examine differences over time.

Results
The trunk muscle endurance declined after the throwing task. In the eighth inning, compared with the first inning, the thoracic rotation angle at the SFC increased toward the throwing side. In contrast, the shoulder horizontal adduction angle at MER decreased in the seventh and ninth innings.

Conclusion
With repeated pitching, trunk muscle endurance gradually declines, and repetitive throwing significantly altered kinematics of the thoracic rotation at SFC and shoulder horizontal plane at MER.

Level of Evidence
2a

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INTRODUCTION

Baseball is one of the most popular sports in Japan, and on average, shoulder injuries occur in baseball players at a rate of 13%–35%.\textsuperscript{1–4} Additionally, it is difficult for an athlete to recover from a shoulder injury and resume their preinjury performance levels. After undergoing surgery for intrinsic shoulder impingement, Peduzzi et al.\textsuperscript{5} evaluated the effects of getting back into sports. However, 120 of 135 patients (90%) who underwent surgery returned to their athletic activities thereafter, with 52% engaging in the same sports at the same level. Only 48% of pitchers who received surgical therapy for superior labral lesions could resume playing, according to Fedoriw et al.,\textsuperscript{6} and only 7% of participants maintained their performance level. Considering all these factors, it is important to investigate the risk factors for shoulder injuries, as these are often multifactorial.\textsuperscript{3,7,8} Among them, repetitive throwing has recently been in focus.\textsuperscript{5,9} In 2014, the Major League Baseball published the Pitch Smart guidelines.\textsuperscript{10} These guidelines include specific pitch count limits, such as 120 pitches per day for athletes aged 19–22 years. Additionally, Murray et al.\textsuperscript{11} showed that the maximum shoulder external rotation angle during pitching decreased because of repetitive throwing. Chou et al.\textsuperscript{12} found that after 100 repeated tosses by high school baseball pitchers, their shoulder horizontal adduction angles at their maximum shoulder external rotation positions (MER) increased. Escamilla et al.\textsuperscript{13} reported that shoulder kinematics did not change after 105–135 pitches. According to these studies, there is no agreement on how repetitive throwing alters the shoulder’s kinematics. Few studies have examined how the shoulder kinematics change with repeated throwing; therefore, further research is required.

When someone pitches, motion and energy are transferred from the lower extremities to the upper extremity in what is known as a kinetic chain.\textsuperscript{14} For the upper extremities to move smoothly and stay injury-free, the thoracic spine, which sits between the lower and upper extremities, must be controlled, which requires strong trunk muscles.\textsuperscript{15} Aguinaldo et al.\textsuperscript{16} investigated the connection between pitching-related thoracic movement and shoulder joint strain. In the early cocking phase, Aguinaldo et al.\textsuperscript{16} suggested that early thoracic rotation enhanced shoulder rotational force and speculated that early thoracic rotation may contribute to throwing-related overuse injuries. Furthermore, according to Douoguih et al.,\textsuperscript{17} early thoracic rotation during the early cocking phase was linked to a noticeably increased risk of upper extremity injuries that required surgery.

Although thoracic movement control is essential to prevent shoulder injury, changes in thoracic kinematics occur during pitching. Therefore, all adverse effects of recurrent throwing on trunk muscle function should be examined.

This study aimed to determine the effects of pitching repeatedly on the endurance of trunk muscles and kinematics of the thoracic spine and shoulder. After repeated tossing, hypothesized that the trunk muscular function would decline and the throwing action would change.

MATERIALS AND METHODS

PARTICIPANTS

Twelve healthy male recreational baseball players were recruited to participate in this study. Players who had previously injured upper or lower extremities injuries or who had shoulder pain at the time of testing were excluded. The study protocol was approved by the Research Ethics Committee. Informed consent was obtained from all the participants.

EXPERIMENTAL PROTOCOL

The repetitive throwing task and measurement protocol are shown in Figure 1. The repetitive throwing task was based on the reports of Dale et al.\textsuperscript{18} and Yanagisawa and Taniguchi.\textsuperscript{19} All participants were allowed five minutes to warm up and stretch using their preferred routine before the repetitive throwing task (i.e., shoulder and trunk stretching and plyometrics). Next, they threw 155 fastballs (~9 innings with 15 throws per inning at ball intervals of 15 seconds) at maximum effort from the set position toward the target. The distance between the pivot foot of the participants and the target was set at 5 m, and the size of the target was $1.1 \times 1.1 \text{ m}$. The target was placed on the extension line of the force plate that was used during 3D motion capture (Figure 2). An official baseball (ZETT Corporation, Osaka, Japan) that weighed 145.0–147.0 g was used during the repetitive throwing task. Five minutes were provided as rest time between each inning.

Before and following the repetitive throwing motion, trunk muscular function was assessed. The throwing motion was monitored during the 1st, 2nd, and 3rd pitches (1st inning), the 103rd, 104th, and 105th pitches (7th inning), the 118th, 119th, and 120th pitches (8th inning), and the 133rd, 134th, and 135th pitches (9th inning). Additionally, the ball speed was measured using a radar gun (Pocket Radar; Pocket Radar Inc., Santa Rosa, CA USA) while assessing the throwing motion. An analysis of ball velocity was performed to ensure that the ball speed had not dropped. Moreover, ball velocity did not drop in all innings (1st inning, 54.1 ± 6.7 mph; 7th inning, 55.6 ± 6.1 mph; 8th inning, 55.6 ± 5.5 mph; 9th inning, 56.9 ± 6.4 mph).

TRUNK MUSCLE ENDURANCE ASSESSMENT

Trunk muscle endurance was measured using a stopwatch (ADME001; Seiko Watch Corporation, Tokyo, Japan) for flexion (Figure 3a), extension (Figure 3b), and throwing and nonthrowing lateral flexion (Figure 3c).\textsuperscript{20–22} The measurement of trunk muscle endurance used in this study is straightforward, and the reliability of the measurement is high.\textsuperscript{20,21} The trunk flexion muscle endurance was measured in the supine position with the hips and knees flexed at 90° and arms crossed over the chest. It was timed after the participant bent their trunk so that both elbows met the front of their thighs and when both elbows left the thighs. Trunk extension muscle endurance was assessed in the prone position with the pelvis aligned with the edge of
Effects of Repetitive Pitching on Trunk Muscle Endurance and Thoracic and Shoulder Kinematics

**Figure 1. Repetitive throwing task and experimental protocol**

The repetitive throwing task was conducted for nine innings with 15 pitches per inning. Trunk muscle endurance was measured before and after the repetitive throwing task. The throwing motion was measured in the first, seventh, eighth, and ninth innings.

**MOTION ANALYSIS**

Throwing motions were measured using a three-dimensional motion analysis system (Vicon MX; Vicon Motion Systems Ltd., London, UK), which utilizes nine infrared strobe cameras and two force plates (BP400600-OP-2K-STT; Advanced Mechanical Technology, Inc., Watertown, MA, USA). Data were captured at 1000Hz, and force plate data were collected at 1000Hz. Thirty-nine reflective markers were fixed to anatomic landmarks according to the Plug-In Gait model (Vicon Motion Systems Ltd.) (spinosus process of the 7th cervical vertebra, spinous process of the 10th thoracic vertebra, sternal notch, xiphoid process, right scapula, bilateral anterior/posterior head, acromioclavicular joint, lateral upper arm, lateral humeral epicodyle, lateral forearm, radial/ulnar styloid, second metacarpal head, anterior/posterior superior iliac spine, lateral thigh, lateral femoral condyle, lateral shank, lateral malleolli, second metatarsal head, and calcaneus). The thoracic angles (anterior/posterior tilt, throwing/nonthrowing side lateral tilt, and nonthrowing/throwing side rotation) and shoulder angles (horizontal adduction/abduction, abduction/adduction, and internal/external rotation) at stride foot contact during the early cocking phase (SFC) and at the maximum shoulder external rotation position during the late cocking phase (MER) were calculated based on the Vicon Plug-In Gait model. The SFC was defined as the instant when the vertical ground reaction force from the nonthrowing side foot exceeded 10 N, and the MER was determined using the joint angle data. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 13.4 Hz. The axes were defined as fol-

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**Figure 2. Laboratory setup**

The distance from the pivot foot position to the target was set at 5 m. The pivot foot position was on the force plate located at the back.

the bed and arms crossed over the chest. The participants kept their trunk parallel to the floor and the time until failure to preserve this trunk position. The trunk lateral flexion muscle endurance was measured in the side-lying position, with the shoulder abducted at 90° and elbow flexed at 90°. Participants maintained a straight position, and the duration between failures to maintain these postures failures were recorded.
RESULTS

Twelve athletes participated in this study (mean age, 22.8 ± 2.9 years; mean body mass, 67.5 ± 8.7 kg; mean height, 170.4 ± 5.4 cm; mean experience, 15.6 ± 1.9 years) (Table 1).

Changes in the trunk muscle endurance before and after repetitive throwing are shown in Table 2. Endurance of the trunk flexors \( p = 0.001, d = 1.10 \) (95% CI: 5.8,10.6), extensors \( p = 0.002, d = 1.30 \) (95% CI: 5.7,12.8), lateral flexors on the throwing side \( p < 0.001, d = 1.11 \) (95% CI: 6.0,11.7), and lateral flexors on the nonthrowing side \( p < 0.001, d = 1.76 \) (95% CI: 7.1,15.7) were significantly decreased after repetitive throwing.

Table 3 shows thoracic spine and shoulder kinematics at SFC and MER in the first, seventh, eighth, and ninth innings. The thoracic rotation angle at the SFC in the eighth inning was significantly lower than that in the first inning \( p = 0.013, d = 0.20 \) (95% CI: 0.4,3.0). The shoulder horizontal adduction angle at MER in the seventh \( p = 0.013, d = 0.38 \) (95% CI: 0.7,4.7) and ninth \( p = 0.004, d = 0.42 \) (95% CI: 1.1,4.6) innings was significantly lower than that in the first inning. No differences were found in other variables.

DISCUSSION

Because shoulder injuries related to pitching occur in 15%-35% of baseball players,1–4 and the likelihood of performance recovery is low,5,6 the link between repetitive throwing and shoulder injury has recently come under scrutiny.3,9 There is a lack of consensus agreement on specific changes that repetitive throwing might cause in shoulder kinematics.11–15 While the most agree that good trunk function is essential in controlling shoulder kinematics, the changes in thoracic kinematics and trunk muscle strength related to repetitive pitching are unclear.15 The results of the current study reveal that the trunk muscle endurance

STATISTICAL ANALYSIS

IBM SPSS Statistics, version 23 (IBM Corp., Armonk, NY, USA) was used for statistical analysis. Shapiro and Wilk’s W-statistic was used to screen all data for normality of distribution. The paired t-test or Wilcoxon signed-rank test was used to compare trunk muscle endurance before and after throwing, depending on whether normality was present or not. The changes in kinematics were analyzed in innings 7, 8, and 9, depending on normality, and the significance level was adjusted by Bonferroni analysis for multiple comparisons. Statistical significance was set at \( p < 0.05 \). Effect sizes and 95% (CI) between each measure were also calculated. Effect sizes (Cohen’s \( d \)) using the paired t-test were rated small \((0.20 \leq d < 0.50)\), moderate \((0.50 \leq d < 0.80)\), and large \((d \geq 0.80)\). Effect sizes (\( r \)) using the Wilcoxon signed-rank test were rated small \((0.10 \leq r < 0.30)\), moderate \((0.30 \leq r < 0.50)\), and large \((r \geq 0.50)\).26

RESULTS

Twelve athletes participated in this study (mean age, 22.8 ± 2.9 years; mean body mass, 67.5 ± 8.7 kg; mean height, 170.4 ± 5.4 cm; mean experience, 15.6 ± 1.9 years) (Table 1).
Effects of Repetitive Pitching on Trunk Muscle Endurance and Thoracic and Shoulder Kinematics

Figure 4. Coordinate system for the thoracic segment and definition of thoracic rotation

- a. Coordinate system; b. definition of thoracic rotation
- C_l: laboratory coordinate system; C_T: thoracic coordinate system.
- X_L, X-axis of C_L; Y_L, Y-axis of C_L; Z_L, Z-axis of C_L.
- The thoracic angle was defined as an absolute angle with respect to a coordinate system, with the flat floor in the laboratory as a reference plane. The rotation to the nonthrowing side was taken as a positive value for the rotation angle of the thoracic (in the case of right-handed throws, the left rotation was taken as a positive value).

Table 1. Characteristics of the participants (n = 12)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22.8 ± 2.9</td>
<td>20–28</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>67.5 ± 8.7</td>
<td>57–85</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>170.4 ± 5.4</td>
<td>165–180</td>
</tr>
<tr>
<td>Experience (years)</td>
<td>13.6 ± 2.9</td>
<td>11–16</td>
</tr>
</tbody>
</table>

SD, standard deviation

Table 2. Data regarding trunk muscle endurance before and after repetitive throwing

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before</th>
<th>After</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk muscle endurance (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>22.7 ± 7.3</td>
<td>15.5 ± 5.7</td>
<td>0.001</td>
</tr>
<tr>
<td>Extension</td>
<td>32.9 ± 7.2</td>
<td>24.7 ± 5.3</td>
<td>0.002</td>
</tr>
<tr>
<td>Lateral flexion in the throwing side</td>
<td>23.9 ± 8.4</td>
<td>15.0 ± 7.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Lateral flexion in the nonthrowing side</td>
<td>25.9 ± 8.1</td>
<td>14.5 ± 4.3</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation.

diminished and thoracic rotation and shoulder horizontal plane kinematics were altered by repetitive throwing.

Despite studies on how shoulder and hip muscle function changes when throwing repeatedly, measurements in trunk muscle function have not yet been examined. In this line, Mullaney et al.27 showed that shoulder internal rotation strength decreased after about 100 pitches, whereas Yanagisawa and Taniguchi19 showed that hip adduction and abduction strength decreased after 117 pitches. Although the body segments assessed varied, the current study conforms to previous reports.

Hirashima et al.28 examined the rectus abdominis and external oblique muscles activity during throwing using surface electromyography. They showed that the external oblique muscles on the nonthrowing side were active in inhibiting early thoracic rotation during the early cocking phase. In contrast, the external oblique muscles on the throwing side were active to direct the thorax toward the throwing direction during the late cocking phase. However, the rectus abdominis muscle was shown to be active immediately before ball release. The paraspinal muscles have been described as active from SFC to ball release for postural control of the trunk.29 Based on these observations, the authors of the current study hypothesized that abdominals and trunk extensors were engaged to control the thoracic movement during each phase of throwing and that repeated throwing reduced trunk muscle endurance.

Early thoracic rotation at the SFC is one of the thoracic kinematics during throwing that should be focused on since it is frequently linked to shoulder injury.16,17 Although trunk muscle endurance decreases occurred in this trial, the thoracic rotation angle to the nonthrowing side at the SFC did not increase. In healthy participants, the decrease in trunk muscle endurance might not necessarily lead to poor trunk motion, such as early thoracic rotation. However, the thoracic rotation angle at the SFC increased toward the throwing side in the eighth inning. The variations observed in this study do not have therapeutic relevance.
because no reports demonstrate a connection between the changes in thoracic kinematics exhibited herein and shoulder injury.

The shoulder horizontal adduction angle at MER dropped in the seventh and ninth innings. However, the effect size for the change in shoulder horizontal adduction angle with recurrent throwing was small in this study. Several studies have focused on how repetitive throwing affects the shoulder’s horizontal adduction angle. Chou et al.\textsuperscript{12} showed that 100 pitches increased the shoulder horizontal adduction angle at the MER in top-level high school baseball players. Conversely, Escamilla et al.\textsuperscript{13} showed that 105–135 repetitive throws did not change the shoulder horizontal adduction angle in Division I college baseball players. Considering factors that lead to a decrease in the shoulder horizontal adduction angle at MER, Mullaney et al.\textsuperscript{27} reported that the shoulder internal rotation strength decreased after 100 pitches. Additionally, Dale et al.\textsuperscript{18} showed that fatigue of the shoulder internal rotator muscles began even after 60 pitches. Throwing repeatedly is likely to reduce the shoulder internal rotation strength because the subscapularis, pectoralis major, and latissimus dorsi muscles are very active from the late cocking phase to the acceleration period.\textsuperscript{30} Jobe\textsuperscript{31} considered that a decrease in the function of the shoulder anterior components may contribute to a decrease in the shoulder horizontal adduction angle during the late cocking phase. Furthermore, of the subscapularis, pectoralis major, and latissimus dorsi muscles, the subscapularis and pectoralis major are thought to contribute to the maintaining of the glenohumeral joint.

Table 3. Thoracic and shoulder kinematics in each inning

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>7th</th>
<th>8th</th>
<th>9th</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SFC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoracic angle (degrees)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior tilt</td>
<td>2.7 ± 9.3</td>
<td>−3.5 ± 6.7</td>
<td>2.0 ± 10.4</td>
<td>1.5 ± 9.6</td>
</tr>
<tr>
<td>p-value</td>
<td>0.073</td>
<td>0.836</td>
<td>0.702</td>
<td></td>
</tr>
<tr>
<td>Lateral tilt</td>
<td>−4.9 ± 6.8</td>
<td>−1.9 ± 9.2</td>
<td>−6.8 ± 5.8</td>
<td>−4.8 ± 5.7</td>
</tr>
<tr>
<td>p-value</td>
<td>0.424</td>
<td>0.122</td>
<td>0.971</td>
<td></td>
</tr>
<tr>
<td>Rotation</td>
<td>−13.7 ± 8.7</td>
<td>−15.5 ± 8.8</td>
<td>−15.4 ± 8.3</td>
<td>−14.5 ± 10.6</td>
</tr>
<tr>
<td>p-value</td>
<td>0.017</td>
<td>0.013</td>
<td>0.541</td>
<td></td>
</tr>
<tr>
<td><strong>Shoulder angle (degrees)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal adduction</td>
<td>−26.7 ± 15.8</td>
<td>−29.8 ± 14.8</td>
<td>−28.8 ± 15.4</td>
<td>−28.2 ± 15.0</td>
</tr>
<tr>
<td>p-value</td>
<td>0.125</td>
<td>0.323</td>
<td>0.422</td>
<td></td>
</tr>
<tr>
<td>Abduction</td>
<td>75.7 ± 18.4</td>
<td>74.3 ± 17.4</td>
<td>73.4 ± 17.0</td>
<td>74.5 ± 17.3</td>
</tr>
<tr>
<td>p-value</td>
<td>0.443</td>
<td>0.352</td>
<td>0.595</td>
<td></td>
</tr>
<tr>
<td>Internal rotation</td>
<td>−24.7[−48.9,−13.0]</td>
<td>−19.0[−31.7,3.7]</td>
<td>−12.0[−47.3,6.4]</td>
<td>−20.4[−39.3,−4.2]</td>
</tr>
<tr>
<td>p-value</td>
<td>0.019</td>
<td>0.041</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td><strong>MER</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoracic angle (degrees)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior tilt</td>
<td>−4.2 ± 20.6</td>
<td>11.2 ± 15.8</td>
<td>9.2 ± 22.0</td>
<td>13.9 ± 17.1</td>
</tr>
<tr>
<td>p-value</td>
<td>0.075</td>
<td>0.118</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>Lateral tilt</td>
<td>18.3 ± 7.9</td>
<td>19.4 ± 12.1</td>
<td>18.5 ± 8.3</td>
<td>18.7 ± 11.0</td>
</tr>
<tr>
<td>p-value</td>
<td>0.791</td>
<td>0.892</td>
<td>0.902</td>
<td></td>
</tr>
<tr>
<td>Rotation</td>
<td>100.4 ± 6.9</td>
<td>102.3 ± 10.4</td>
<td>100.5 ± 6.6</td>
<td>99.7 ± 6.9</td>
</tr>
<tr>
<td>p-value</td>
<td>0.447</td>
<td>0.970</td>
<td>0.636</td>
<td></td>
</tr>
<tr>
<td>Shoulder angle (degrees)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal adduction</td>
<td>9.2 ± 6.7</td>
<td>6.6 ± 7.0</td>
<td>7.0 ± 6.5</td>
<td>6.4 ± 6.6</td>
</tr>
<tr>
<td>p-value</td>
<td>0.013</td>
<td>0.035</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Abduction</td>
<td>97.9 ± 9.4</td>
<td>98.4 ± 9.9</td>
<td>98.7 ± 10.6</td>
<td>98.4 ± 10.7</td>
</tr>
<tr>
<td>p-value</td>
<td>0.563</td>
<td>0.475</td>
<td>0.655</td>
<td></td>
</tr>
<tr>
<td>Internal rotation</td>
<td>−147.9 ± 14.7</td>
<td>−149.8 ± 15.0</td>
<td>−150.2 ± 15.5</td>
<td>−150.6 ± 16.4</td>
</tr>
<tr>
<td>p-value</td>
<td>0.146</td>
<td>0.122</td>
<td>0.031</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation and medians and interquartile. \[] indicates interquartile.
Each variable was compared in the 1st vs. 7th inning, 1st vs. 8th inning, and 1st vs. 9th inning.
MER = maximum external rotation during the late cocking phase; SFC = stride foot contact during the early cocking phase.
horizontal adduction position.\textsuperscript{30} However, although there were no changes in thoracic kinematics affecting shoulder kinematics in this study, a deficit in muscle function of the anterior shoulder components, such as the subscapularis and pectoralis major muscles, may lead to a change in the shoulder horizontal plane kinematics at MER.

A decreased shoulder horizontal adduction angle at MER is closely associated with shoulder injuries and is a risk factor for posterior superior impingement syndrome.\textsuperscript{31,32} Posterior superior impingement syndrome is a phenomenon in which the rotator cuff is trapped between the humeral head and glenoid fossa during the late cocking phase.\textsuperscript{31,32} Mihata et al.\textsuperscript{33} reproduced the MER position in cadaveric shoulders and reported that the pressure between the greater tuberosity and glenoid increased as the shoulder horizontal adduction angle decreased. In this study, the shoulder horizontal adduction angle at MER decreased in the seventh and ninth innings, suggesting that pitching >100 pitches may contribute to increased mechanical stress within the shoulder.

This study has some limitations. First, the trunk muscle endurance was evaluated using a method that is easy to use in clinical and field situations. However, the technique used in this study could not deny subjectivity. In the future, we should employ a more accurate method of assessment. Second, the throwing motion function was only assessed during specific innings. Japanese starting pitchers often throw more than seven innings, but in the United States, they barely reach this number. Whether the throwing motion will change in less than seven innings needs to be determined. Therefore, assessing pitching data in every inning would be relevant, particularly in American baseball. Third, based on previous reports, the authors speculate that the decreased shoulder horizontal adduction angle at MER increases mechanical stress within the shoulder.\textsuperscript{31–33}

This study only showed changes in shoulder motion with repetitive throwing in healthy participants, and whether a healthy athlete whose shoulder motion is altered by repetitive throwing will develop shoulder injuries in the future remains unknown. If the relationship between changes in shoulder motion with repeated throwing and the incidence of shoulder injury can be clarified, this may lead to preventive actions for future injuries.

**CONCLUSION**

The results of this study indicate that with 135 repeated throws trunk muscular endurance was reduced. In addition, thoracic rotation at SFC and shoulder horizontal plane at MER kinematics were altered by repetitive throwing.

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DISCLAIMERS

No potential conflict of interest was reported by the authors.

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Elbow Injuries Among MLB Pitchers Increased During Covid-19 Disrupted Season, But Not Other Baseball Injuries

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Keywords: Professional Baseball, Elbow Injuries, Injury Surveillance

Background
The 2020 Major League Baseball Season (MLB) demonstrated season disruptions due to the COVID-19 pandemic. Changes in training and seasonal time frames may be associated with higher rates of injury.

Purpose
To use publicly available data to compare injury rates during the 2015-2019 seasons, COVID-19 shortened season (2020), and the 2021 season stratified by body region and position (pitchers versus position players).

Study Design
A retrospective cohort study utilizing publicly available data

Methods
MLB players who competed in 1+ seasons between 2015-2021 were included and stratified by position (pitcher, position player). Incidence rate (IR), reported by 1000 x Athlete-Game Exposures (AGEs), was calculated for each season, and stratified by position and body region. Poisson regressions were performed for all injuries and stratified by position to determine association between season and injury incidence. Subgroup analyses were performed on the elbow, groin/hip/thigh, shoulder.

Results
Four thousand, two hundred and seventy-four injuries and 796,502 AGEs across 15,152 players were documented. Overall IR was similar across seasons (2015-2019:5.59; 2020:5.85; 2021:5.04 per 1000 AGEs). IR remained high for the groin/hip/thigh for position players (2015-2019:1.7; 2020:2.0; 2021:1.7 per 1000 AGEs). There was no difference in injury rates between 2015-2019 and 2020 seasons [1.1 (0.9-1.2), p=0.310]. The 2020 season demonstrated a significant increase in elbow injuries [2.7 (1.8-4.0), p<0.001]; when stratified by position, this increase remained significant for pitchers [pitchers: 3.5 (2.1-5.9), p<0.001; position players: 1.8 (0.9-3.6), p=0.075]. No other differences were observed.

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Conclusion

The groin/hip/thigh demonstrated the highest IR in 2020 among position players across all season time frames, indicating that continued injury mitigation for this region is necessary. When stratified by body region, elbow injury rates among pitchers demonstrated 3.5 times the rate of injury in 2020 compared to previous seasons, impacting injury burden for the most vulnerable body region among pitchers.

Level of Evidence

Level III

INTRODUCTION

Major League Baseball (MLB) is the professional baseball league in North America representing 30 teams in the United States and Canada. Standard season format consists of six weeks of pre-season spring training, 162 game regular season, and a ten team post-season format. Over the course of a typical season, injury incidence rates have ranged between 0.7-5.13 per 1000 athlete exposures (AEs) across all positions. These injuries result in significant league wide missed playing time and monetary losses; previous analyses have estimated the cost of placing players on the disabled list to be between $136-695 million per year between 1998 to 2015. Due to the physical and financial burden associated with MLB injuries, baseball stakeholders including coaches, owners, players, and clinicians have sought to mitigate injuries. A systematic approach to injury prevention research has been suggested by van Mechelen, beginning with injury surveillance to increase understanding of incidence rate over time.

In contrast to the standard season layout, the 2020 MLB season format was disrupted due to the COVID-19 pandemic. Pre-season spring training was cancelled and four months later resumed in a condensed two-to-three-week format. The regular season was condensed to a 60 game schedule over two months, with an expanded 16 team post season schedule. This schedule adjustment increased the number of double headers played within the season and decreased the number of rest days. Disruption to pre-season training, inconsistent training regimens, isolation requirements for players who tested positive for COVID-19, decreased equipment access, and increased schedule density likely impacted players ability to manage training and playing loads. One study investigating injury incidence during the COVID-19 shortened MLB season demonstrated an increased injury incidence rate compared to the previous season (2020 season: 8.66 per 1000 AEs; 2019 season: 5.13 per 1000 AEs). Previous studies across multiple professional leagues including the National Basketball Association, National Football League, European professional soccer leagues, have also reported an increase in injury rates during the 2020 shortened season. However, most of these studies reported comparisons to a single previous season. Sparse information is available on previous five season data, which may be more representative of injury rate (IR trends), or on the subsequent 2021 season to determine if IR stabilized the following year. Furthermore, previous injury surveillance literature among professional leagues during the 2020 COVID-19 season reported injuries based on anatomic zones versus recommended standardized reporting by body region/area, or reported on a single pathology, making comparison to previous literature difficult.

One way to identify injury incidence among MLB players is through publicly available data. Publicly available data improves transparency, and allows for collaboration among organizations to improve data robustness and distribution among stakeholders. This transparency and collaboration amongst organizations is essential to promote an open science environment. An open science approach allows researchers to independently assess, reproduce, and perform studies for further independent research with data that is easily accessible. Publicly available data is an example of data that is in line with this open science recommendation, and has been utilized across professional leagues with a high reporting reliability. Publicly available data is accessed through a computer iterative repeatable process which involves an automated collection of information from webpages, an efficient method of data extraction. This process improves repeatability, and offers the potential for collaborative league wide injury risk identification and injury mitigation programs. The primary aim of this study was to use publicly available data to compare injury rates during the 2015-2019 seasons, COVID-19 shortened season (2020), and the 2021 season stratified by body region and position (pitchers versus position players).

METHODS

STUDY DESIGN

This was a retrospective cohort study among MLB players utilizing publicly available data through a computer iterative reproducible method that has been previously described. Two data repositories were used to create a data set for this study (Supplemental File 1). The data can be accessed through the Open Science Framework data repository. MLb stakeholders (coaches, sports medicine clinicians, and performance coaches) were included to aid in development of the research question and clinical interpretability of the results. This study was reported following the Strengthening the Reporting of Observational Studies in Epidemiology for Sport Injury and Illness Surveillance (STROBE-SIIS) guideline.

International Journal of Sports Physical Therapy
PARTICIPANTS

Participants were MLB players 18 years or older who competed in at least one season between 2015 to 2021 seasons. For subgroup analyses, players were labeled as a pitcher (starters, middle relievers, relievers) or position player (infield, outfield, catcher, designated hitter) for injury incidence comparisons.

INJURY CLASSIFICATION

Injuries were included in this study that occurred from the first game of the regular season to the last game of the post season during team sanctioned events, including games or practices. Injuries that occurred during the preseason or off-season were not included due to inconsistencies observed in the data and inability to corroborate if injuries occurred during team sanctioned events. Injury was defined as any tissue damage or derangement of normal physical function that occurred during a training session or competition that resulted in time loss of one or more days. Injury was defined based on a specific joint or body segment as recommended by STROBE-SIIS body region and area guidelines.  

ATHLETE EXPOSURE

Seasons were defined as 2015-2019 season, COVID-19 shortened season (2020), and 2021 season. Athlete exposure was calculated based on game exposure (AGE) only as determining practice exposure was not possible with this data set. For the 2015-2019 seasons, AGEs were calculated based on all 30 MLB teams playing 162 regular season games per season, 25-man active roster, over the five seasons. For 2020 season, rule changes to roster size took effect two weeks into the season. Thus, AGEs were calculated based on 30 MLB teams playing 60 regular season games, a 30 man roster the first two weeks, 28 man roster the second two weeks, and a 26-man roster for the remaining weeks of play. For 2021 season, AGEs were calculated based on 30 MLB teams playing 162 regular season games per season and a 26-man roster. For all seasons, a postseason exposure adjustment was included to account for post season injuries based on the number of playoff games that occurred each season, with a reduction in the number of active players as teams were eliminated.

DATA EXTRACTION, DATA REDUCTION AND EXTERNAL VALIDATION

For a detailed description of data repository used refer to Supplemental File 1. Data were extracted on November 3, 2021. Data extraction, data reduction, and external validation used have been previously described. External validation was performed by two independent examiners using a number generator, randomly selected 100 data points from the data set. External validation was performed for date of injury and injury type for each selected player from other publicly available websites (i.e., ESPN.com, mlb.com, team websites). 83% of randomly selected records were confirmed in outside reports demonstrating excellent reliability for injury reporting. Refer to Supplemental File 1 and 2 for detailed methods and data extraction code.

STATISTICAL ANALYSES

Injury and illness count data was converted to seasonal incidence rate (IR). IR was calculated by sum of injuries and divided by the sum of player-games, multiplied by 1000 x Athlete–Game Exposures (AGEs) and adjusted for number of regular and post-season games each year. IR for overall injuries for in-season time frame was calculated by adjusting for monthly AGEs. Rate ratios (RR) were calculated by specific position incidence rate (pitcher or position player) and divided by all other position incidence rate for pre 2015-2019 seasons, COVID-19 shortened season (2020), and 2021 season. A Poisson Regression was performed to investigate the potential differences in injury rates between season time frames (2015-2019; 2020; 2021). AGE was used as an offset for the model to control for differences in athlete exposure each year. Poisson models were performed for all injuries and stratified by position (pitchers and position players). Additional exploratory models were performed on the most commonly injured body regions, including the shoulder, elbow, and groin/hip/thigh region and stratified by position. All analyses were performed in R version 4.1.3 (R Core Team, 2020) using the rvest, tm, and xml2 packages.

RESULTS

INJURY INCIDENCE ALL POSITIONS

Between 2015 to 2021 seasons, 4,274 injuries were documented across 796,502 AGEs. The 2015-2019 seasons incidence rate was 5.4 per 1000 AGEs overall, followed by an increase to 5.9 per 1000 AGEs during the 2020 COVID-19 shortened season, before decreasing to 5.0 per 1000 AGEs during the 2021 season (Table 1). By month, the IR peaked and was higher during the first two months in 2020 (month 1: 8.2 per 1000 AGEs, month 2: 7.9 per 1000 AGEs), compared to 2015-2019 (month 1: 4.5 per 2000 AGEs, month 2: 5.8 per 1000 AGEs) and 2021 (month 1: 5.6 per 1000 AGEs, month 2: 7.5 per 1000 AGEs) (Figure 1). Compared to previous years, the IR remained elevated in month 1 (5.6 per 1000 AGEs), and month 2 (7.5 per 1000 AGEs) compared to first two months in 2015-2019 (Figure 1).

INJURY INCIDENCE AMONG PITCHERS

For pitchers the highest IR was observed in 2020 at 2.2 per 1000 AGEs compared to the 2015-2019 (1.9 per 1000 AGEs), and 2021 (1.0 per 1000 AGEs) seasons. By body region, the highest elbow injury IR of 0.7 per 1000 AGEs compared to 2015-2019 (elbow: 0.2 per 1000 AGEs), and 2021 (elbow: 0.1 per 1000 AGEs) seasons (Table 2). Pitchers demonstrated an increased risk of 5.5 (95% CI: 2.1, 6.0) of sustaining an elbow injury during the COVID-19 shortened season compared to the previous five seasons (Supplemental File 3).
Table 1. Overall Injury Incidence Rate

<table>
<thead>
<tr>
<th>Position</th>
<th>Seasons</th>
<th>Number of Injuries</th>
<th>Incidence Rateb</th>
<th>95% CIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Positions</td>
<td>2015-2019</td>
<td>3325</td>
<td>5.39</td>
<td>5.21, 5.58</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>303</td>
<td>5.85</td>
<td>5.19, 6.51</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>646</td>
<td>5.04</td>
<td>4.65, 5.42</td>
</tr>
<tr>
<td>Pitchers</td>
<td>2015-2019</td>
<td>593</td>
<td>1.85</td>
<td>1.70, 2.00</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>57</td>
<td>2.20</td>
<td>1.63, 2.77</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>63</td>
<td>0.98</td>
<td>0.74, 1.22</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>245</td>
<td>9.47</td>
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<tr>
<td></td>
<td>2021</td>
<td>583</td>
<td>9.09</td>
<td>8.35, 9.83</td>
</tr>
</tbody>
</table>

b Incidence rate was calculated per 1000 Athlete Game Exposures

Figure 1. Overall Injury Incidence Rate by Month

Incidence rate was calculated per 1000 Athlete Game Exposures;
AGE: Athlete Game Exposures

INJURY INCIDENCE AMONG POSITION PLAYERS

For position players the highest overall IR was observed in 2020 at 9.5 injuries per 1000 AGEs compared to 2015-2019 (9.1 per 1000 AGEs), and 2021 (9.0 per 1000 AGEs) seasons. During the 2020 season, the groin/hip/thigh (2.0 per 1000 AGEs) was the most commonly injured body regions during the COVID-19 shortened season; these IRs were elevated compared to the 2015-2019 (groin/hip/thigh: 1.7 per 1000 AGEs) and 2021 (groin/hip/thigh: 1.7 per 1000 AGEs) seasons (Table 3). Although elbow injuries were less commonly reported in position players, elbow injuries were observed the highest in 2020; position players, with a RR of 1.8 (95% CIs: 1.0-3.6) times more likely to acquire an elbow injury during the 2020 shortened season compared to 2015-2019; this risk remained elevated in 2021 compared to 2015-2019 season (1.6, 95% CIs: 1.0, 2.6) (Supplemental File 3).

POISSON REGRESSION

Across all injuries and positions, Poisson regression results revealed no difference in injury rates between 2015-2019 and 2020 seasons (1.195% CIs: 0.9, 1.2, p = 0.310) but a reduction occurred in the 2021 season compared to the
Table 2. Pitchers Injury Incidence Rate by Body Region

<table>
<thead>
<tr>
<th>Body Region</th>
<th>Season</th>
<th>Number of Injuries</th>
<th>Incidence Rate&lt;sup&gt;b&lt;/sup&gt;</th>
<th>95% CIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>2015-2019</td>
<td>13</td>
<td>0.04</td>
<td>0.02, 0.06</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>1</td>
<td>0.04</td>
<td>-0.04, 0.11</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>0</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Lower Leg</td>
<td>2015-2019</td>
<td>15</td>
<td>0.05</td>
<td>0.02, 0.07</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>2</td>
<td>0.08</td>
<td>-0.03, 0.18</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>3</td>
<td>0.05</td>
<td>-0.01, 0.10</td>
</tr>
<tr>
<td>Knee</td>
<td>2015-2019</td>
<td>29</td>
<td>0.09</td>
<td>0.06, 0.12</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>2</td>
<td>0.08</td>
<td>-0.03, 0.18</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>4</td>
<td>0.06</td>
<td>0.00, 0.12</td>
</tr>
<tr>
<td>Leg</td>
<td>2015-2019</td>
<td>15</td>
<td>0.05</td>
<td>0.02, 0.07</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>0</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>1</td>
<td>0.02</td>
<td>-0.01, 0.05</td>
</tr>
<tr>
<td>Groin/Hip/Thigh</td>
<td>2015-2019</td>
<td>66</td>
<td>0.21</td>
<td>0.16, 0.26</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>4</td>
<td>0.15</td>
<td>0.00, 0.31</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>7</td>
<td>0.11</td>
<td>0.03, 0.19</td>
</tr>
<tr>
<td>Hand</td>
<td>2015-2019</td>
<td>46</td>
<td>0.14</td>
<td>0.10, 0.18</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>4</td>
<td>0.15</td>
<td>0.00, 0.31</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>5</td>
<td>0.08</td>
<td>0.01, 0.15</td>
</tr>
<tr>
<td>Wrist</td>
<td>2015-2019</td>
<td>9</td>
<td>0.03</td>
<td>0.01, 0.05</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>0</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>1</td>
<td>0.02</td>
<td>-0.01, 0.05</td>
</tr>
<tr>
<td>Forearm</td>
<td>2015-2019</td>
<td>25</td>
<td>0.08</td>
<td>0.05, 0.11</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>4</td>
<td>0.15</td>
<td>0.00, 0.31</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>2</td>
<td>0.03</td>
<td>-0.01, 0.07</td>
</tr>
<tr>
<td>Elbow</td>
<td>2015-2019</td>
<td>63</td>
<td>0.20</td>
<td>0.15, 0.25</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>18</td>
<td>0.70</td>
<td>0.37, 1.02</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>4</td>
<td>0.06</td>
<td>0.00, 0.12</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>2015-2019</td>
<td>19</td>
<td>0.06</td>
<td>0.03, 0.09</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>2</td>
<td>0.08</td>
<td>-0.03, 0.18</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>4</td>
<td>0.06</td>
<td>0.00, 0.12</td>
</tr>
<tr>
<td>Shoulder</td>
<td>2015-2019</td>
<td>76</td>
<td>0.24</td>
<td>0.18, 0.29</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>3</td>
<td>0.12</td>
<td>-0.02, 0.25</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>7</td>
<td>0.11</td>
<td>0.03, 0.19</td>
</tr>
<tr>
<td>Head/Neck</td>
<td>2015-2019</td>
<td>36</td>
<td>0.11</td>
<td>0.08, 0.15</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>3</td>
<td>0.12</td>
<td>-0.02, 0.25</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>2</td>
<td>0.03</td>
<td>-0.01, 0.07</td>
</tr>
<tr>
<td>Trunk/Back/Buttock</td>
<td>2015-2019</td>
<td>91</td>
<td>0.28</td>
<td>0.23, 0.34</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>11</td>
<td>0.42</td>
<td>0.17, 0.68</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>4</td>
<td>0.06</td>
<td>0.00, 0.12</td>
</tr>
</tbody>
</table>

<sup>b</sup> Incidence rate was calculated per 1000 Athlete Game Exposures

2015-2019 seasons (0.9, 95% CIs: 0.8, 1.0 p = 0.046). The 2020 season saw an increase in elbow injuries during the 2020 season compared to 2015-2019 seasons (2.7, 95% CIs: 1.8, 4.0, p < 0.001); when stratified by position, this increase
<table>
<thead>
<tr>
<th>Body Region</th>
<th>Season</th>
<th>Number of Injuries</th>
<th>Incidence Rate&lt;sup&gt;b&lt;/sup&gt;</th>
<th>95% CIs</th>
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</thead>
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<td>0.30, 0.44</td>
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<td>0.10, 0.52</td>
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<tr>
<td></td>
<td>2021</td>
<td>24</td>
<td>0.37</td>
<td>0.22, 0.52</td>
</tr>
<tr>
<td>Lower Leg</td>
<td>2015-2019</td>
<td>91</td>
<td>0.31</td>
<td>0.24, 0.37</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>9</td>
<td>0.35</td>
<td>0.12, 0.57</td>
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<td>2021</td>
<td>29</td>
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<tr>
<td>Knee</td>
<td>2015-2019</td>
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<td>18</td>
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<td>0.37, 1.02</td>
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<td>Leg</td>
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<td>0.12, 0.21</td>
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<td></td>
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<td>0.19</td>
<td>0.02, 0.36</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>24</td>
<td>0.37</td>
<td>0.22, 0.52</td>
</tr>
<tr>
<td>Groin/Hip/Thigh</td>
<td>2015-2019</td>
<td>498</td>
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<td>1.54, 1.83</td>
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<td></td>
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<td>1.43, 2.51</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>110</td>
<td>1.71</td>
<td>1.39, 2.04</td>
</tr>
<tr>
<td>Hand</td>
<td>2015-2019</td>
<td>282</td>
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<td>0.84, 1.06</td>
</tr>
<tr>
<td></td>
<td>2020</td>
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<td>0.62, 1.39</td>
</tr>
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<td></td>
<td>2021</td>
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</tr>
<tr>
<td>Wrist</td>
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<tr>
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<td>2020</td>
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<td>0.70</td>
<td>0.37, 1.02</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>38</td>
<td>0.59</td>
<td>0.40, 0.78</td>
</tr>
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<td>Forearm</td>
<td>2015-2019</td>
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<td>0.08, 0.16</td>
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<td></td>
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<td>2021</td>
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<td>0.04, 0.21</td>
</tr>
<tr>
<td>Elbow</td>
<td>2015-2019</td>
<td>62</td>
<td>0.21</td>
<td>0.16, 0.26</td>
</tr>
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<td></td>
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<td>0.15, 0.63</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>21</td>
<td>0.33</td>
<td>0.19, 0.47</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>2015-2019</td>
<td>15</td>
<td>0.05</td>
<td>0.03, 0.08</td>
</tr>
<tr>
<td></td>
<td>2020</td>
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<td>0.04</td>
<td>-0.04, 0.11</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>4</td>
<td>0.06</td>
<td>0.00, 0.12</td>
</tr>
<tr>
<td>Shoulder</td>
<td>2015-2019</td>
<td>144</td>
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<td>0.41, 0.57</td>
</tr>
<tr>
<td></td>
<td>2020</td>
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<td>0.42</td>
<td>0.17, 0.68</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>22</td>
<td>0.34</td>
<td>0.20, 0.49</td>
</tr>
<tr>
<td>Head/Neck</td>
<td>2015-2019</td>
<td>203</td>
<td>0.69</td>
<td>0.59, 0.78</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>12</td>
<td>0.46</td>
<td>0.20, 0.73</td>
</tr>
<tr>
<td></td>
<td>2021</td>
<td>29</td>
<td>0.45</td>
<td>0.29, 0.62</td>
</tr>
<tr>
<td>Trunk/Back/Buttock</td>
<td>2015-2019</td>
<td>415</td>
<td>1.40</td>
<td>1.27, 1.54</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>2021</td>
<td>94</td>
<td>1.47</td>
<td>1.17, 1.76</td>
</tr>
</tbody>
</table>

<sup>b</sup> Incidence rate was calculated per 1000 Athlete Game Exposures

only remained significant for pitchers in 2020 (pitchers: 3.5 95% CIs: 2.1, 6.0, p < 0.001; position players: 1.8 95% CI: 0.8, 3.6, p = 0.03)
1.0, 3.6, p = 0.073). No other differences were observed in the shoulder or groin/hip/thigh. Refer to Supplemental File 4 for further Poisson regression analyses results.

DISCUSSION

Injury rates were similar during the COVID-19 shortened season among pitchers and position players compared to the 2015-2019 and 2021 seasons for combined injuries. Specific to body region, pitchers demonstrated the highest IR for the elbow during the 2020 with the elbow demonstrating an increase in 3.5 times the rate compared to the previous five seasons. Among position players, the groin/hip/thigh was the most commonly injured body region during the COVID-19 shortened season at 2.0 per 1000 AGEs; however, this difference was not significantly different from the pre-COVID-19 seasons.

OVERALL INJURY INCIDENCE

Injury rates increased minimally during the 2020 season, but not to a clinically meaningful level compared to 2015-2019 and 2021 season. Notably, the IR during the first two months of the season demonstrated peak IR that was higher than the first two months of 2015-2019 season IR. During the COVID-19 shortened season, players experienced a delayed and condensed spring training, a period of time in which MLB players are usually able to gradually increase their skill specific workload prior to the regular season.8 Access to training facilities after the postponement of spring training was variable prior to the delayed start of spring training in July 2020.8 Once resumed, spring training was reduced to two to three weeks, less than half the allotted time compared to previous seasons.8 Additionally, a condensed schedule (60 games in two months, versus 162 games in six months) with an expanded post season (16 versus eight teams) occurred, increasing the amount of doubleheaders played in a season with decreased rest days.8 Furthermore, COVID-19 isolation protocols restricted players from playing or training once they tested positive to prevent the spread COVID-19, likely having a de-training effect on individual players.8 Although protocols were in place throughout the league, abrupt cancellations due to COVID-19 outbreaks amongst teams likely impacted training regimens and game schedules.8 Despite these abrupt changes in routine among players, overall injury rates were not significantly different based on crude injury rates or the Poisson model results. Only one study was identified that investigated IR changes among MLB players comparing 2019 and 2020 IR across multiple body regions.5 Platt BN et al confirmed the current findings that injury rates increased during the COVID-19 shortened 2020 season compared to previous seasons.5 However, Platt BN et al demonstrated a higher IR in 2020 compared to the current results (8.66 per 1000 AEs versus 5.84 per 1000 AGEs), and regression modeling strategies were not performed impacting the ability to control for variation in athlete exposure for seasonal comparisons. The differences in IR noted may also be due to varying season time frame comparisons (2019, versus 2015-2019 and 2021) or differences in exposure calculation (AGE versus AE); furthermore, our study accounted for post-season AGEs which may have attributed to our lower IR reported. However, external validation was performed and reported in this study which demonstrated excellent reliability for injury reporting improving clinical interpretability. Further studies investigating incidence rates stratified by season time frame and body region are recommended to determine if specific body regions are impacted at varying times of the season by changes to preseason or season formats.

INJURY INCIDENCE AMONG PITCHERS

The elbow demonstrated the highest injury incidence among pitchers during the 2020 season, representing an increase of 3.5 times the rate of the previous five seasons. Elbow injuries often lead to significant disability among MLB pitchers, leading to highest number of days on the MLB Injury List.27 In a 2017 study examining 15 seasons from 1998-2015, 30% of elbow injuries among MLB pitchers were season ending, 28.4% involved ligamentous structures, and pitchers that incurred an elbow injury lead to surgery more often than position pitchers (pitchers: 40% versus position players: 17.6%).27 The baseball pitching motion places substantial forces at the elbow, at upwards of 115 N/m.28-30 The structures at the elbow working to resist these high forces at the elbow are static structures including the ulnar collateral ligament working in conjunction with dynamic structures such as the flexor carpi ulnaris, two structures often implicated at the elbow when pathology occurs.31 Furthermore, kinematic variables including shoulder abduction angle,22 timing and amount of trunk rotation and lateral tilt,28,32 play a role in forces measured at the elbow. However, as a pitcher presents with fatigue via acute work load changes, kinematic variable changes have been documented. Electromyographic activation of the flexor carpi ulnaris decreases,31 maximum external rotation decreases, and knee extension at ball release decreases. These kinematic and EMG activation changes likely contribute to the subsequent decrease ball velocity in a single extended pitch outing.33 The influence of fatigue on kinematic variables, change to spring training schedule, and the increased density of games played during the 2020 season may have played a role in the increased incidence rate of elbow injuries observed,8 despite the in season changes to expand roster size during the 2020 season.3 Sports clinicians should carefully monitor pitchers for changes in pitch volume that acutely increase or are sustained for longer bouts of time and implement appropriate recovery and injury mitigation strategies to minimize elbow injuries.

INJURY INCIDENCE AMONG POSITION PLAYERS

During the COVID-19 shortened season, the groin/hip/thigh demonstrated the greatest IR by body region among position players at 2.0 per 1000 AGEs; this body region is often the most commonly reported injury site among position players in previous seasons.34 Previous literature demonstrates a similar AE for combined lower extremity
injuries at 2.0 per 1000 AEs.\textsuperscript{3} Amongst major and minor league players during the 2011-2016 season, hamstring strains were the most commonly reported pathology.\textsuperscript{34} Other injuries reported among baseball players to this region include extra-articular injuries such as adductor and quadriceps muscle strains or avulsions, and contusions; intra-articular injuries can also occur including labral abnormalities and femoral acetabular impingement.\textsuperscript{35} Groin/hip/thigh injuries can occur during acute bouts of quick acceleration or deceleration moments during base running or fielding, or via cumulative sport demands of repetitive fielding, throwing, batting, representing longer chronicity of symptoms.\textsuperscript{35} Although there is an elevation in IR in the groin/hip/thigh region observed during the COVID-19 shortened season compared to previous seasons, the results of the Poisson regression did not demonstrate this to be statistically significant, likely due to the wide and overlapping 95\% CIs reported. However, it is notable to consider the potential detraing effects as impacted by density and disruption of the 2020 game schedule and isolation protocols that may have influenced recovery and training strategies contributing to the groin/hip/thigh injuries reported.\textsuperscript{8} Detraing of type II muscle fibers occur in as little as two weeks of inactivity, and 8\% of one rep max strength decreases have been shown after one month of detraining periods.\textsuperscript{36} These disruptions may have also impacted acute and chronic workload increases compared to previous seasons.\textsuperscript{37–40} Increased cumulative training workloads have been previously associated with susceptibility to overtraining syndrome\textsuperscript{0,41} and acute injury\textsuperscript{25,42} which may have influenced the IR seen in the groin/hip/thigh.

**CLINICAL IMPLICATIONS**

This study and previous literature provide a framework for injury surveillance, the first step in the sequence of injury prevention recommended by van Mechelen and colleagues.\textsuperscript{7} Furthermore, this paper informs baseball stakeholders on the resulting injury burden when abrupt changes in season and training occur (i.e. COVID-19 pandemic, seasonal lockouts during negotiations) followed by an accelerated return to sport. Although the differences in overall injury incidence may not be clinically significant, players are at the highest risk for the most vulnerable injuries, particularly the elbow among pitchers, and groin/hip/thigh injuries among position players. By investigating the 2021 season, which demonstrated decreases in injury incidence, this allows for strong pre and post season comparisons when abrupt seasonal changes occur. Longer periods of ramp up with titrated loading strategies, coinciding with targeted elbow and thigh injury prevention programs may allow for improved recovery and injury mitigation strategies needed to combat the increased risk for acute elbow and groin/hip/thigh injuries during return to baseball following abrupt cessation of sport such as the COVID-19 pandemic or other work stoppage scenarios.\textsuperscript{2,40}

**LIMITATIONS**

This study is not without limitations. Only MLB players were assessed, decreasing generalizability of the results to other professional baseball leagues or amateur baseball players. Further, the public data set utilized does not allow for missing data to be quantified, which may impact the precision of these results. However, external data validation was performed with other publicly available data to increase the interpretability of these results. Additionally, injuries were classified by IOC standard labels to the nearest anatomical body part\textsuperscript{14}; injuries reported based on pathology (i.e. ulnar collateral ligament tear, hamstring strain, oblique strain) were inconsistently reported, decreasing the potential clinical interpretability of these findings. Finally, an estimated player-game exposures were used to calculate IR based on typical games played each season. Athletes by position may have different exposure to sport, which was not possible to calculate with these data, impacting the clinical interpretability of these findings.

**CONCLUSION**

Combined injury rates were similar during the Covid-19 shortened 2020 season among all positions compared to the 2015-2019 and 2021 seasons. By body region, the elbow was the most commonly injured body region in 2020 among pitchers, with the elbow demonstrating an increase in 3.5 times the rate compared to the previous five seasons. Among position players, the groin/hip/thigh demonstrated the highest IR in 2020. Baseball stakeholders may consider longer periods of ramp up and loading strategies; these loading strategies may allow for improved recovery and injury mitigation strategies following training disruptions. Injury mitigation strategies should give attention to the most vulnerable injuries, particularly the elbow and groin/hip/thigh region among all MLB players.

**CONFLICT OF INTEREST**

The authors report no conflict of interest.

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REFERENCES


Original Research

Upper Quarter Injury Rates and Risk in United States High School Athletes Prior To and During the Prolonged Sport Stoppage

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Keywords: Coronavirus, Loading, Upper Extremity, Natural Experiment, Interrupted Time Series

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Background
Upper quarter injuries are a serious problem in high school sports. The distinctive differences in males and females and within sports concerning specific upper quarter body parts necessitates the need to evaluate these injuries across these groups. The COVID-19 pandemic has created an opportunity to evaluate the potential added burden abrupt and prolonged sport stoppage had on upper quarter injury risk.

Hypothesis/Purpose
To 1) describe and compare upper quarter injury rates and risk in high school athletes in the 2019-2020 and 2020-2021 academic school years; 2) examine injuries by gender, sport, injury type, and location of injury.

Methods
An ecological study of the athletes from 176 high schools over six states, matching high schools between 2019-2020 (19-20) and 2020-2021 (20-21) years was performed. Injuries were reported by at least one high school athletic trainer assigned to each school into a centralized database and data collected from July 1, 2019, to June 30, 2021. Injury rates were calculated per 1,000 athletes per academic year. Interrupted time series models assessed the incidence ratio between academic years.

Results
A total of 98,487 athletes from all sports participated in 19-20 and 72,521 in 20-21. Upper quarter injury rates increased in from 19-20 [41.9 (40.6, 43.1)] to 20-21 [50.7 (48.1, 51.3)]. Upper quarter injury risk [1.5 (1.1, 2.2)] was greater in 20-21 compared to 19-20. Females did not demonstrate increased injury rates between 19-20 [31.1 (29.4, 32.7)] to 20-21 [28.1 (26.4, 30.0)]. Males reported increased injury rates from 19-20 [50.3 (48.5, 52.2)] to 20-21 [67.7 (65.2, 70.2)]. Increased injury for the shoulder, elbow, and hand were reported in 20-21. Collision, field, and court upper quarter injury rates were increased in 20-21.

Discussion
Upper quarter injury rates and injury risk were greater during the 2020-2021 school year than in the prior year. Males demonstrated increased upper quarter injury rates, while females did not. Return to play protocols for high school athletes should be considered following abrupt sport stoppage.

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Level of Evidence

INTRODUCTION

Upper quarter injuries are a serious problem in high school athletes, with 21% of all athletic injuries sustained to the upper extremity. Almost 600,000 acute traumatic arm fractures occur annually, representing one in ten of all injuries sustained in high school athletes annually. The highest incidence of upper extremity injury is in the shoulder and elbow, with almost half of adolescent upper quarter injuries occurring at the shoulder. Upper quarter injuries have a high medical burden, costing over $15,000 per injury in high school athletes.

There are distinct differences in high school athlete upper quarter injury incidence between genders, with male high school athletes more likely to suffer severe injuries compared to females. When comparing similar sports between high school males and females, males have a greater prevalence of upper quarter injuries, with up to 2.04 times greater odds and 18.3 upper quarter injuries per 100,000 athletes. Different sports also have dissimilarities in upper quarter incidence. Athletes in collision sports have suffered up to 42% of total injuries to the upper quarter, while athletes in field and court sports have sustained up to 55% of upper quarter injuries.

The escalation of COVID-19 infections within the United States led to the cancellation of high school sports, beginning in March 2020. The sudden and prolonged interruption of high school practices and competition led to decreased physical activity and sport training over time. This sport-specific training and competition stoppage resulted in decreased cardiovascular fitness, strength and power, potentially increasing musculoskeletal injury risk during return to sport the following academic year. The interruption of high school sport practice and competition, coinciding with the COVID-19 pandemic, provides a distinct chance to evaluate upper quarter injury patterns in high school athletes following an abrupt sport stoppage. While COVID-19 is the exact mechanism for sport stoppage, this provides an opportunity to consider the effects of abrupt sport stoppage on upper quarter injury incidence and risk, when resuming sport.

There are currently no studies comprehensively evaluating upper quarter injury that occur in high school sports. The distinctive differences in males and females, and within sports concerning specific upper quarter joints, necessitates the evaluation of injuries across these groups. The COVID-19 pandemic has created an opportunity to evaluate the potential added burden abrupt and prolonged sport stoppage has on upper quarter injury risk. Therefore, the purpose of this study was to describe and compare upper quarter injury rates and risk in high school athletes in the 2019-2020 and 2020-2021 academic school years; examine injuries by gender, sport, injury type, and location of injury.

MATERIALS AND METHODS

STUDY DESIGN

An ecological study on high school upper quarter injuries was performed. The Strengthening the Reporting of Observational Studies in Epidemiology for Sport Injury and Illness Surveillance (STROBE-SIIS) were followed (Please see STROBE checklist as supplement). This study was approved by the PRISMA Health Institutional Review Board. Data cannot be shared for ethical/privacy reasons.

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 2019-2020 and 2020-2021 academic years. High school matching was based on participating in high school sports during the 2020-2021 academic year. High schools had to at minimum participate in a portion of all three sport seasons (e.g., fall, winter, and spring). If the high school did not report or participate in high school athletics during the 2020-2021 year, they were excluded. This study was an observational study, and all injury records were performed for injury reporting.

DATA COLLECTION

Athlete injuries reported their injuries to the high school athletic trainer. The athletic trainer recorded all injuries by date and recorded time loss during any team-sponsored practices or games. Athlete trainer sport coverage was based on the individual high school sport participation. Data was collected from the regional athletic trainer supervisor and the regional and national quality control supervisors on a quarterly basis.

ATHLETE EXPOSURE

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. Athlete exposure was not calculated for days of school suspension, medical visits that were not musculoskeletal related (e.g., general medical visit), or extramural school activities not related to sport. School holidays and teacher work days (e.g., Thanksgiving and Christmas) and high school or school district level stoppage of in person academic learning and sport partic-
ipation due to COVID-19 were marked and not considered athlete exposure. Due to the ecological nature of this study, it was not possible to obtain individual athlete exposure for epidemiological calculations, only if an athlete sustained a time loss illness or injury that was related to athlete exposure. Exposure was calculated per high school.

INJURY DEFINITION

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 required medical attention.\(^{16}\) Athlete complaints that resulted in cessation of a competition or training session but the athlete returned to training or competition the same session or following day were recorded as zero days of time loss and did not result in a recorded injury.\(^{16}\) Injured body segments and body parts were defined by the Orchard Sports Injury Classification System.\(^{19}\) Due to the nature and mechanism of injury, concussions were excluded from this analyses. Specific anatomic body parts were recorded. Injury type was categorized as a cartilage injury, contusion, dislocation/subluxation/instability, fracture, sprain, strain, or other.\(^{19}\) Injury time loss was calculated in number of days.\(^{16}\) Injury severity was calculated as overall time loss, with injury severity stratified using 8-28 days (moderate) and >28 (severe) days.\(^{16}\)

CONFOUNDERS

Self-identified gender, state, sport, and socioeconomic status were identified as confounders. Socioeconomic status was controlled through 1:1 high school matching between academic years. Due to the large number of sports played, sport was collapsed into four categories: collision (American football, lacrosse, wrestling, ice hockey, rugby), field 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. The category of "other" was utilized for non-descript sport records.

STATISTICAL ANALYSES

All data were assessed for missingness prior to analyses (Gender: 0%; Age: 0%; Date of Injury: 5%; Sport: 1.7%; Body Part: 1.6%; Return to Play: <0.1%), and 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 (percentages) for categorical variables. Injury rates, with 95% confidence intervals (95% CI) was calculated per 1,000 athletes that participated within one academic year (August through March, per matching).\(^6\) Results were stratified by academic year, gender, state, sport, mechanism of injury, and type of injury.

To assess potential differences in upper quarter injury incidence between academic years, a mixed effects negative binomial interrupted time series model with robust errors was performed. Potential excess injuries for the 2020-2021 academic year were calculated on the expected upper quarter injury count from the 2019-2020 year. A dummy variable was included for the 2019-2020 academic year (0) and the 2020-2021 academic year (1). Further, an interaction between academic calendar year and month was included in the model. Random effects were modeled at the high school level. Model fixed effects were controlled using state, school holidays, and seasonality. To account for changes in athlete exposure due to the academic calendar, the number of school holidays, teacher work days, and days lost to COVID-19 exposure per month were included as a continuous variable. Seasonality was controlled for by assessing potential nonlinear relationships between month as a continuous variables and injury incidence through fractional polynomials. Non-linear relationship was observed to be a 2, -2 non-linear term. The log of high school athlete participation was included as an offset. All analyses were performed in R version 4.0.1 (R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/), using the \textit{naniar} package for missingness assessment and the \textit{GLMMadapt} package for zero inflated mixed effects negative binomial modelling.

RESULTS

A total of 98,487 athletes (Female: 43,249; Male: 55,238) participated in high school sport in 2019-2020 and 72,521 athletes (Female: 32,968; Male: 39,553) in the 2020-2021 academic year. A total of 4,125 upper quarter injuries occurred in the 2019-2020 academic year and 3,606 upper quarter injuries in the 2020-2021 academic year. The median time loss suffered from an upper quarter injury was 21 (1, 46) days during the 2019-2020 academic year and 17 (1, 34) days during the 2020-2021 academic year. The median time loss suffered from upper quarter injury for females was 21 (1, 47) days during the 2019-2020 academic year and 16 (1, 33) days during the 2020-2021 academic year. The mean time loss suffered from upper quarter injury for males was 21 (1, 46) days during the 2019-2020 academic year and 17 (1, 35) days during the 2020-2021 academic year.

UPPER QUARTER INJURY RATES AND RISK

There was an overall increase in upper quarter injury rates per 1,000 athletes between the 2019-2020 and 2020-2021 academic years and for males (Table 1). The greatest increase in male upper quarter injury rates were in the category of moderate injuries. For upper quarter injury rates stratified by state, please refer to Appendix 2. Crude analyses demonstrated that upper quarter injuries increased by a ratio of 1.2 [95% CI: 1.1, 1.3], \(p < 0.001\) during the 2020-2021 academic school year. When accounting for calendar month and days lost to shelter in place and school holidays throughout the academic year, upper quarter in-
jury increased by a ratio of 1.5 (95% CI: 1.1, 2.2), p = 0.022] during the 2020-2021 academic school year.

**UPPER QUARTER INJURY RATES BY INJURY TYPES**

The 2020-2021 academic demonstrated increased upper quarter injury rates per 1,000 athletes for contusions, dislocation/subluxation/instability, sprains, and strains compared to the 2019-2020 academic year (Table 2).

**UPPER QUARTER INJURY RATES BY SPORT**

Collision and field and court sports reported increased upper quarter injury rates per 1,000 athletes during the 2020-2021 academic year compared to the 2019-2020 academic year. Individual sport upper quarter injury rates per 1,000 athletes were similar between academic years (Table 3). Injury rates by body part for collision and field and court sports are reported in Appendix 3.

**UPPER QUARTER INJURY RATES BY BODY PART AND ANATOMIC LOCATION**

There were increased shoulder/proximal humerus, elbow, wrist, and hand injury rates per 1,000 athletes in the 2020-2021 compared to the 2019-2020 academic year (Table 4). Concerning shoulder specific injuries, there were increased acromioclavicular, clavicle, labrum, and rotator cuff injury rates per 1,000 athletes in 2020-2021 compared to the 2019-2020 academic year. Concerning elbow injuries, there were increased ulnar collateral ligament injury rates per 1,000 athletes in 2020-2021 compared to the 2019-2020 academic year. Concerning forearm specific injuries, there were increased pronator-flexor mass injury rates per 1,000 athletes in 2020-2021 compared to the 2019-2020 academic year (Table 5).

**DISCUSSION**

The main findings of this study were that there was increased upper quarter injury rates during the 2020-2021 compared to 2019-2020 academic school year. When controlling for confounders, upper quarter injury risk was also increased. Male upper quarter injury rates increased, while female injury rates were similar between academic years. Shoulder, elbow, and hand injury rates increased in the 2020-2021 academic year. Collision and field and court sport upper quarter injury rates increased, while individual sports demonstrated similar injury rates between academic years.

Upper quarter injury rates and risk were greater for the 2020-2021 academic year. This is not surprising considering the long layoff period and delayed return to sport for these high school athletes. High school sport interruption and the sudden subsequent resuming of sport may have influenced the increase in upper quarter injury rates and risk. In a survey of 13,000 high school athletes during the recent high school sport pause, they reported a 20% reduction in physical activity compared to pre-pandemic physical activity levels.20 In another study, high school athletes during the cessation of sport reported performing almost two hours less of strength training, 1.5 hours less of endurance training, and over 6 hours less sport specific training per week.21 A decrease in physical activity and exercise has been recognized as an important injury risk factor in high school physical education students22 and college athletes.14 The resultant deconditioning and lower load tolerance from decreased training may predispose the athlete to excessive loads upon returning to high school sport, potentially increasing upper quarter injury risk.15 Further research is needed to understand the implications of deconditioning and load tolerance on upper quarter injury risk in high school athletes.

Male high school athletes reported increased upper quarter injury rates, compared to female athletes that sustained similar upper quarter injury rates between academic school years. The greatest increase in male injury rates were in the category of moderate injuries. These gender differences may be attributed to potential discrepancies in style of play,7,9,23 sports played,24 or overall gender specific differences in injury risk.23,25,26 Previous researchers have observed that high school male athletes are more likely to sustain severe upper quarter musculoskeletal injuries and traumatic injuries compared to female athletes.27 Male high school athletes are also more likely to suffer head/neck, shoulder, and hand injuries that require surgery compared to females in comparable sports.24 Within high school baseball and softball, male baseball players are more likely to suffer an initial upper extremity injury compared to female softball players.27

Athletes in collision and field and court sports demonstrated increased injury rates during the 2020-2021 academic year. Field and court sports, such as tennis and baseball use the upper extremity for ball propulsion.28 This results in increased upper extremity injury risk.27 However, other field and court sports such as basketball and soccer have demonstrated a high prevalence of shoulder injuries due to player contact and guarding, suggesting moderate upper extremity sport involvement.29 Collision sports such as football, lacrosse, and wrestling have also previously demonstrated high injury prevalence and incidence in high school athletes. Athletes in collision sports are more susceptible to traumatic upper quarter injuries, which may be related to decreased collision physical preparedness as they return to sport.1,8 General decreased upper extremity involvement in individual sports, such as cross country running or track and field, has demonstrated less upper extremity injury prevalence compared to the trunk or lower extremity.30

Shoulder, elbow, and hand/finger injury rates were greater during the 2020-2021 academic year. These findings support previous research, with the shoulder, elbow and hand/finger demonstrating the greatest prevalence in injuries to the upper quarter in high school athletes.7,10,11 Hand/finger injuries are predominantly traumatic fracture injuries,31,32 while shoulder and elbow injuries have previously been identified as traumatic or overuse injuries.7,10,11 Within sport, overuse injuries predominantly occur from...
Table 1. Upper Quarter Injury Rates per 1,000 Athletes per Academic Year by Gender and Severity. All injury rates are reported per 1,000 athletes, with 95% confidence intervals

<table>
<thead>
<tr>
<th></th>
<th>Upper Quarter Injury</th>
<th>Upper Quarter Injury Severity</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19-20</td>
<td>20-21</td>
<td>19-20</td>
<td>20-21</td>
<td>19-20</td>
<td>20-21</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19-20; n = 98,487</td>
<td>41.9</td>
<td>50.7</td>
<td>13.0</td>
<td>14.0</td>
<td>10.7</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>(40.6, 43.1)</td>
<td>(48.1, 51.3)</td>
<td>(12.3, 13.7)</td>
<td>(13.2, 14.9)</td>
<td>(10.1, 11.4)</td>
<td>(16.8, 18.8)</td>
</tr>
<tr>
<td>20-21; n = 72,521</td>
<td>19-20</td>
<td>20-21</td>
<td>19-20</td>
<td>20-21</td>
<td>19-20</td>
<td>20-21</td>
</tr>
<tr>
<td></td>
<td>14.0</td>
<td>17.8</td>
<td>10.7</td>
<td>18.0</td>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(13.2, 14.9)</td>
<td>(16.8, 18.8)</td>
<td>(10.1, 11.4)</td>
<td>(17.2, 18.8)</td>
<td></td>
<td>(16.5, 18.4)</td>
</tr>
<tr>
<td>Female</td>
<td>31.1</td>
<td>28.1</td>
<td>10.2</td>
<td>8.7</td>
<td>7.3</td>
<td>9.5</td>
</tr>
<tr>
<td>19-20; n = 43,250</td>
<td>(29.4, 32.7)</td>
<td>(26.4, 30.0)</td>
<td>(9.3, 11.1)</td>
<td>(7.7, 9.7)</td>
<td>(6.5, 8.1)</td>
<td>(8.4, 10.5)</td>
</tr>
<tr>
<td></td>
<td>20-21; n = 32,968</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>50.3</td>
<td>67.7</td>
<td>16.1</td>
<td>18.5</td>
<td>13.5</td>
<td>24.7</td>
</tr>
<tr>
<td>19-20; n = 55,239</td>
<td>(48.5, 52.2)</td>
<td>(65.2, 70.2)</td>
<td>(14.1, 16.2)</td>
<td>(17.2, 19.8)</td>
<td>(12.5, 14.5)</td>
<td>(23.2, 26.3)</td>
</tr>
<tr>
<td></td>
<td>20-21; n = 39,554</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.7</td>
<td>24.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

19-20 = Pre-pandemic academic year
20-21 = Pandemic academic year
throwing, swinging an implement such as a golf club or tennis racket, or prolonged gripping.35

PRACTICAL CLINICAL IMPLICATIONS

The increase in upper quarter injury rates, most notably in males, and those participating in collision sports, and field and court sports, suggest that return to loading strategies should be considered, and may focus on acclimating athletes to collision (i.e., tackling and blocking) physical demands. Further, athletes in sports with higher upper extremity demands, such as baseball and tennis, should have a slower ramp up for throwing, serving, or other similar sport activities. Sports medicine clinicians should consider educating high school athletes, sport coaches, and their parents on performing gradual increases in training and practices when returning to sport following any unexpected or prolonged sport stoppage. Sports medicine clinicians should also consider creating return to play protocols with high school sport stakeholders in their community, in case of sport stoppages such as natural disasters (i.e., hurricanes, earthquakes), prolonged illness/injury or pandemics to help reduce the risk of upper quarter injuries.

STRENGTHS AND POTENTIAL LIMITATIONS

Athletes from six states, two regions of the United States, and 176 high schools were included in this study, increasing the generalizability of these findings. Upper quarter injuries were stratified by gender, state, sport, injury type, and anatomic body part providing a comprehensive and in depth reporting and analysis of upper quarter injuries in high school athletes. The variability of sports for each high school and state required sport groupings to be collapsed, decreasing the precision in these findings. Due to the ecological nature of this study, training and competition minutes could not be obtained, preventing rate calculations, decreasing the precision in injury incidence analyses. However, the number of days missed due to holidays, workdays, and shelter in place days during the academic school year were controlled for, improving the risk analyses precision. These results may be affected by the potential confounding of selection bias of schools participated in sport participation during the 2020-2021 academic school year. One state reported an increase of over 3,000 students that participated in sports during the 2020-2021 year. The increased sport participation prevalence may be related to the exclusion of other after school activities during the 2020-2021 year. However, the exact cause is not known, increasing selection bias.

CONCLUSION

Upper quarter injury rates were greater for the 2020-2021 academic school year in this sample of high school athletes. When controlling for confounders, models demonstrated increased injury risk for the 2020-2021 academic school year. While males reported increased upper quarter injury rates, females demonstrated comparable injury rates between academic years. Shoulder, elbow, and hand injury rates among all athletes increased in the 2020-2021 academic year. Athletes participating in collision and field and court sports reported an increase in upper quarter injuries, while athletes in individual sports reported similar injury rates for both school years. The results of this research may have implications beyond the COVID-19 pandemic, including natural disasters and work stoppages. Further research is required to understand the generalizability of these findings to different abrupt sport stoppage scenarios and the safe dose response required when returning to training for high school athletes and other competition levels.

### Table 2. Upper Quarter Injury Rates per 1,000 Athletes per Academic Year by Type. Injury rates are reported per 1,000 athletes per academic year, and with 95% confidence intervals.

<table>
<thead>
<tr>
<th>Injury Type</th>
<th>Academic Year</th>
<th>19-20</th>
<th>20-21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(95%)</td>
<td>(95%)</td>
</tr>
<tr>
<td>Cartilage</td>
<td></td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.2, 1.6)</td>
<td>(1.3, 1.9)</td>
</tr>
<tr>
<td>Contusion</td>
<td></td>
<td>4.7</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4.3, 5.1)</td>
<td>(5.3, 6.4)</td>
</tr>
<tr>
<td>Dislocation/Subluxation/Instability</td>
<td></td>
<td>3.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2.7, 3.4)</td>
<td>(4.3, 5.3)</td>
</tr>
<tr>
<td>Fracture</td>
<td></td>
<td>6.4</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5.9, 6.9)</td>
<td>(9.0, 10.5)</td>
</tr>
<tr>
<td>Sprain</td>
<td></td>
<td>11.0</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10.3, 11.6)</td>
<td>(13.1, 14.9)</td>
</tr>
<tr>
<td>Strain</td>
<td></td>
<td>6.0</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5.5, 6.4)</td>
<td>(6.5, 7.7)</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>9.1</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(8.5, 9.7)</td>
<td>(6.0, 7.1)</td>
</tr>
</tbody>
</table>

19-20 = Pre pandemic academic year; Total of 98,487 athletes participated in sport 20-21 = Pandemic academic year; Total of 72,521 athletes participated in sport Other consists of deformity, disorder, laceration, and non-descript injury type records * Injury rates that increased from 2019-2020 to 2020-2021 are bolded

### Table 3. Upper Quarter Injury Rates per 1,000 Athletes per Academic Year by Sport. All injury rates are reported per 1,000 athletes, with 95% confidence intervals.

<table>
<thead>
<tr>
<th>Sport</th>
<th>Academic Year</th>
<th>19-20</th>
<th>20-21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(95%)</td>
<td>(95%)</td>
</tr>
<tr>
<td>Collision</td>
<td></td>
<td>17.1</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.3, 17.9)</td>
<td>(25.0, 27.3)</td>
</tr>
<tr>
<td>Field &amp; Court</td>
<td></td>
<td>12.2</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(11.5, 12.9)</td>
<td>(16.9, 18.9)</td>
</tr>
<tr>
<td>Individual</td>
<td></td>
<td>3.7</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3.3, 4.1)</td>
<td>(3.9, 4.9)</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>8.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(8.3, 9.5)</td>
<td>(1.0, 1.5)</td>
</tr>
</tbody>
</table>

19-20 = Pre pandemic academic year; Total of 98,487 athletes participated in sport 20-21 = Pandemic academic year; Total of 72,521 athletes participated in sport * Injury rates that increased from 2019-2020 to 2020-2021 are bolded
### Table 4. Upper Quarter Injury Rates per 1,000 Athletes per Academic Year by Body Part. All injury rates are reported per 1,000 athletes with 95% confidence intervals

<table>
<thead>
<tr>
<th>Upper Quarter Body Part</th>
<th>Academic Year</th>
<th>19-20</th>
<th>20-21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(4.0, 4.9)</td>
<td>(3.2, 4.1)</td>
</tr>
<tr>
<td>Head/face</td>
<td>4.4</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Cervical</td>
<td>3.5 (3.2, 3.9)</td>
<td>2.0 (1.6, 2.3)</td>
<td></td>
</tr>
<tr>
<td>Shoulder/Proximal Humerus</td>
<td>15.8 (15.0, 16.6)</td>
<td>19.8 (18.8, 20.8)</td>
<td></td>
</tr>
<tr>
<td>Elbow</td>
<td>4.0 (3.6, 4.4)</td>
<td>5.1 (4.6, 5.6)</td>
<td></td>
</tr>
<tr>
<td>Forearm</td>
<td>1.0 (0.8, 1.2)</td>
<td>1.5 (1.2, 1.8)</td>
<td></td>
</tr>
<tr>
<td>Wrist</td>
<td>4.0 (3.6, 4.4)</td>
<td>6.0 (5.4, 6.5)</td>
<td></td>
</tr>
<tr>
<td>Hand/Finger</td>
<td>9.1 (8.5, 9.7)</td>
<td>11.7 (11.0, 12.5)</td>
<td></td>
</tr>
</tbody>
</table>

19-20 = Pre pandemic academic year; Total of 98,487 athletes participated in sport
20-21 = Pandemic academic year; Total of 72,521 athletes participated in sport
*Injury rates that increased from 2019-2020 to 2020-2021 are bolded

### Table 5. Injury Rates per 1,000 Athletes per Academic Year by Anatomic Region or Diagnosis for Shoulder and Elbow Injuries. All injury rates are reported per 1,000 athletes, with 95% confidence intervals

<table>
<thead>
<tr>
<th>Anatomic Region or Diagnosis</th>
<th>19-20 n = 98,487</th>
<th>20-21 n = 72,521</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acromioclavicular (AC) Joint</td>
<td>1.5 (1.2, 1.7)</td>
<td>2.3 (1.9, 2.6)</td>
</tr>
<tr>
<td>Bicep</td>
<td>0.9 (0.7, 1.1)</td>
<td>1.5 (1.2, 1.8)</td>
</tr>
<tr>
<td>Clavicle</td>
<td>0.6 (0.4, 0.7)</td>
<td>1.3 (1.0, 1.5)</td>
</tr>
<tr>
<td>Glenohumeral Joint</td>
<td>2.2 (1.9, 2.5)</td>
<td>2.5 (2.1, 2.9)</td>
</tr>
<tr>
<td>Labrum</td>
<td>0.9 (0.8, 1.1)</td>
<td>1.9 (1.5, 2.2)</td>
</tr>
<tr>
<td>Neurovascular</td>
<td>0.2 (0.1, 0.3)</td>
<td>0.5 (0.3, 0.6)</td>
</tr>
<tr>
<td>Rotator Cuff</td>
<td>3.5 (3.2, 3.9)</td>
<td>5.9 (5.3, 6.4)</td>
</tr>
<tr>
<td>Scapula</td>
<td>0.3 (0.2, 0.4)</td>
<td>0.4 (0.2, 0.5)</td>
</tr>
</tbody>
</table>

Elbow

<table>
<thead>
<tr>
<th></th>
<th>19-20</th>
<th>20-21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olecranon</td>
<td>0.1 (0.05, 0.2)</td>
<td>0.1 (0.04, 0.2)</td>
</tr>
<tr>
<td>Neurovascular</td>
<td>0.1 (0.02, 0.2)</td>
<td>0.2 (0.1, 0.3)</td>
</tr>
<tr>
<td>Pronator-Flexor Mass</td>
<td>0.5 (0.4, 0.7)</td>
<td>1.3 (1.0, 1.5)</td>
</tr>
<tr>
<td>Radius</td>
<td>0.2 (0.1, 0.3)</td>
<td>0.3 (0.2, 0.4)</td>
</tr>
<tr>
<td>Triceps</td>
<td>0.2 (0.1, 0.3)</td>
<td>0.3 (0.2, 0.4)</td>
</tr>
<tr>
<td>Ulna</td>
<td>0.1 (0.06, 0.2)</td>
<td>0.2 (0.1, 0.3)</td>
</tr>
<tr>
<td>Ulna Humeral Joint</td>
<td>0.3 (0.2, 0.4)</td>
<td>0.3 (0.2, 0.4)</td>
</tr>
<tr>
<td>Ulnar Collateral Ligament</td>
<td>0.6 (0.5, 0.8)</td>
<td>1.2 (0.9, 1.4)</td>
</tr>
</tbody>
</table>

19-20 = Pre pandemic academic year
20-21 = Pandemic academic year
*Injury rates that increased from 2019-2020 to 2020-2021 are bolded

CONFLICT OF INTEREST
The authors have no conflicts of interest

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REFERENCES


SUPPLEMENTARY MATERIALS

Appendix 1

Appendix 2

Appendix 3
Elbow Injuries Among MLB Pitchers Increased During Covid-19 Disrupted Season, But Not Other Baseball Injuries

SUPPLEMENTARY MATERIALS

Supplemental Files
Missing The Forest For The Trees: A Lack Of Upper Extremity Physical Performance Testing In Sports Physical Therapy

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1 Department of Physical Therapy, University of Illinois at Chicago, 2 Department of Physical Therapy, Baylor University, 3 Physical Therapy, Universidade Federal de Minas Gerais, 4 Department of Physical Therapy and Human Movement Sciences, Northwestern University

Keywords: upper extremity, return to sport, shoulder, elbow, physical performance

Background
Despite shoulder and elbow injuries being common in athletics, return to sport and reinjury rates are less than ideal. These outcomes may be driven by the absence of evidence-informed testing to determine an athlete's readiness for sport.

Purpose
The purpose of this study was to explore the reported frequency of physical performance testing for return to sport readiness by physical therapists treating athletes with upper extremity injuries and to identify potential barriers that may limit use of these tests. A secondary aim was to compare practice patterns of clinicians with sports physical therapy specialty certification to clinicians without.

Study Design
International, cross-sectional survey using purposive sampling.

Methods
A survey instrument was created to assess the frequency of use of physical performance tests by physical therapists treating athletes with upper extremity injuries, as well as the barriers limiting the use of these tests. The 19-question online survey was distributed via email and Twitter among sports physical therapists. Independent t-tests and Chi Square analyses were conducted to determine differences in practice patterns between physical therapists with and without specialization and the frequency of potential barriers that may limit the use of these tests.

Results
Four hundred ninety-eight participants met study eligibility and completed the survey. Fewer than half of participants reported using any physical performance test in making return to sport decisions for athletes with upper extremity injuries. The greatest barriers to the use of physical performance tests were a lack of equipment followed by lack of understanding of the literature, lack of time, and lack of supporting literature. Sports specialist clinicians were significantly more likely (p<0.001) to use physical performance tests than non-specialist clinicians (71.6% versus 36.5%).

Conclusion
In this survey of physical therapists (n=498), the majority admit to not using physical performance tests when making return to sport decisions for athletes with upper extremity injuries regardless of specialization.

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Physical therapists have an opportunity to improve the utilization physical performance testing in the upper extremity athlete in hopes of reducing injury recurrence and enhance return to sport rates.

**Level of Evidence**

**Level 3b**

**INTRODUCTION**

Injuries to the shoulder and elbow are commonplace in the athletic population and regularly occur in both contact and non-contact sports. In contact and collision sports such as American football, rugby, hockey and soccer, the shoulder accounts for up to 20% of all injuries, most commonly acromioclavicular joint sprains and glenohumeral instability.1–5 In college athletes attending the National Football League (NFL) combine, reported prevalence of previous shoulder injuries is 50–52%.1,6 In overhead sports such as baseball, softball, volleyball, tennis, swimming, and water polo, the shoulder accounts for 17-35% of all musculoskeletal injuries, most commonly involving labral and rotator cuff pathology.7–11 In baseball and softball athletes alone, elbow injury is also a significant source of disability accounting for up to 22% of injuries.12–14 Despite high upper extremity injury rates, athletes often seek care with the goal of returning to sport and pre-injury levels of performance.

The proportion of athletes who are successfully able to return to sport following upper extremity injury varies based on the injury type and surgical status. In athletes with shoulder instability, 40–88% of athletes managed non-operatively15–17 and 86–90% managed with surgical stabilization were able to successfully return to sport.18,19 However, only 50–75% of athletes return to sport at their previous level following surgical intervention,18,19 When considering overhead athletes with ulnar collateral ligament (UCL) injuries, 85–95% of athletes managed non-operatively and 75-100% of athletes managed with surgical reconstruction were able to successfully return to sport.20–22 However, only 84–95% of athletes managed non-operatively and 65–90% of those managed surgically returned to their previous level of competition.20–22

Recurrence rates for upper extremity injuries vary based on injury type and surgical status as well. The rate of reinjury after shoulder stabilization surgery has been found to be as high as 23%, but can be reduced to 10% with a comprehensive rehabilitation program.18,23,24 Following UCL reconstruction, revision rates are ultimately low (1–7%) but in a study following the outcomes of 147 athletes after UCL reconstruction, 26% of athletes returned to the injured list at some point in their career due to additional elbow injuries.25,26 These varied and less-than-ideal outcomes in return to sport and reinjury rates may be driven, in part, by the absence of an evidence-informed battery of tests used to determine an athlete’s physical performance and readiness for sport, ultimately resulting in athletes returning to sport before they achieve full physical performance of the involved upper extremity and kinetic chain.25,27

Physical performance tests, defined as assessments in which an athlete performs a physical task believed to be a component of a sports activity, can provide insight into an athlete's readiness for return to sport.28 In athletes recovering from lower extremity injuries, the passing of physical performance tests (e.g., hop testing, agility testing) has been found to be effective in decreasing reinjury.29–32 However, current evidence on return to sport outcomes following upper extremity injury is comparatively lacking and limited to case series and clinical commentary.25,33 It is possible that this lack of outcomes research on the utility of upper extremity physical performance tests may be attributed to a lack of clinical use. If clinicians do not use upper extremity performance tests to make return to sport readiness decisions, there may be large variance in return to sport decision making and higher recurrence risk for upper extremity injuries in sports. Therefore, the purpose of this study was to explore the reported frequency of physical performance testing for return to sport readiness by physical therapists treating athletes with upper extremity injuries and the perceived potential barriers that may limit the use of these tests. A secondary aim of this study was to compare the practice patterns of clinicians with a sports physical therapy specialty certification to clinicians without this certification. The authors hypothesized that the majority of clinicians do not utilize upper extremity physical performance tests with their athletic patient population, and that the greatest barriers to their use would be a lack of awareness and understanding of current available evidence.

**METHODS**

**SURVEY CONTENTS**

A survey instrument was created to assess the frequency of use of physical performance tests by physical therapists treating athletes with upper extremity injuries, as well as the perceived barriers limiting the use of these tests. (Appendix) A team of three physical therapists highly experienced in the management of upper extremity athletes collaborated to develop the electronic survey using Qualtrics software (Qualtrics, Provo, UT). The development team reviewed and tested the survey among themselves, after which face and content validity were assessed by piloting the survey among a group of eight physical therapists. Feedback was gathered on the survey and modifications were completed in order to enhance survey clarity and functionality. The survey was designed to be completed in 5-10 minutes.

The survey was separated into three sections. Section I gathered information regarding the country the participant was currently practicing in, their years of experience, and specialty certifications as recognized by the International
Table 1. Clinical criteria evaluated using the International Classification of Function, Disability, and Health (ICF) framework

<table>
<thead>
<tr>
<th>Contextual Factors</th>
<th>Impairments</th>
<th>Activity Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timeline from Injury</td>
<td>Range of motion</td>
<td>Seated Shot-Put Test</td>
</tr>
<tr>
<td>Patient’s self-reported readiness for return to sport</td>
<td>Manual muscle testing</td>
<td>Closed Kinetic Chain Upper Extremity Stability Test</td>
</tr>
<tr>
<td>Patient Reported Outcome Measures (FOTO, DASH, WOSI, ASES, KJOC, etc.)</td>
<td>Hand-held dynamometry</td>
<td>Upper Quarter Y-Balance Test</td>
</tr>
<tr>
<td></td>
<td>Isokinetic testing</td>
<td>Timed Pushup Test</td>
</tr>
<tr>
<td></td>
<td>Proprioception</td>
<td>One Arm Hop Test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Athletic Shoulder Test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shoulder Arm Return to Sport</td>
</tr>
</tbody>
</table>

Federation of Sports Physical Therapy. Section II assessed the participant's percentage of patient population that included patients with shoulder and/or elbow injuries, as well as those that had goals that included unrestricted return to sport. Specific clinical information grouped by the International Classification of Function, Disability, and Health (ICF) framework was assessed for utilization (Table 1). Participants were also asked if their testing battery changed based on the sport that the athlete was returning to and whether they would like to use more physical performance testing in their discharge planning. Section III of the survey investigated the participant’s reported barriers limiting the use of physical performance tests to assess activity limitations, the estimated percentage of patients who pass all pre-established physical performance tests prior to discharge, as well any reasons why patients are discharged prior to passing the physical performance tests. Categorical data were used for the frequency of patients passing all physical performance tests with responses of 25% or less considered “rarely,” 26 to 50% considered “sometimes,” 51% to 75% considered “frequently,” and greater than 75% of patients considered “consistently.” The survey instrument is available in APPENDIX 1.

The Consensus-Based Checklist for Reporting of Survey Studies (CROSS) guidelines were followed. All survey materials were approved prior to survey distribution by the Institutional Review Board at Baylor University (IRB# 1690575). Participants provided online consent before participating in the study. Inclusion criteria for survey participants were as follows: active, licensed physical therapist; currently treating in a sports or orthopaedic setting. All but three participants completed the survey in its entirety, failing to document their years of experience. However, all data captured was included in the data analysis.

SURVEY DISTRIBUTION

The study design was an international, cross-sectional survey using purposive sampling. The 19-question online survey was distributed via email and social media (Twitter) among sports physical therapists. The survey was sent to members of the American Academy of Sports Physical Therapy (sent to 6,797 members), International Federation of Sports Physical Therapy (14,350 members), American Society of Shoulder and Elbow Therapists (106 members), and the European Society for Shoulder and Elbow Rehabilitation (517 members). One reminder was sent to each membership organization one month after the initial email to maximize response rates. The survey was written in English and was accessible between December 2020 and April 2021.

STATISTICAL ANALYSES

Data were analyzed with SAS statistical software (JMP 16.3, Cary, NC). Participating physical therapist demographics were compared between those with and without sports specialization. Independent t-tests and Chi Square analyses were conducted to determine differences in practice pattern use of physical performance tests by physical therapists with and without specialization and the frequency of potential barriers that may limit the use of these tests. Significance was set at p=.05 with a Bonferroni adjustment to account for multiple comparisons.

RESULTS

Over the four-month collection period, 703 surveys were initiated with 512 being completed with consent (72.83% completion rate). Of those 512 participants, 498 were actively treating patients in a sports or orthopaedics setting (Figure 1). Of the 498 included participants, the mean years of clinical experience reported was 13.1(SD 10.6). The majority of participants (85.1%) were actively treating in the United States (n=424) and 14.9% were actively treating outside of the United States (n=74). Fewer participants (26.9%, n=154) had a sports specialization recognized by their respective country compared to 73.1% (n=364) of participants without. Of all participants, 70% (n=350) estimated that at least a quarter of their patient population present with shoulder or elbow injuries, and 56% (n=218) of participants estimated that at least a quarter of their patients with shoulder or elbow injuries have a goal of return to sport.
INFORMATION USED IN RETURN TO SPORT DECISIONS

Using the ICF framework, results for the frequency of items used to make return to sport decisions are shown in Table 2. The most commonly reported factors used by physical therapists to make return to sport decisions using the ICF framework were: 1) impairments identified with range of motion and manual muscle tests, and 2) contextual factors such as patient subjective readiness to return to sport and patient reported outcome measures. Nearly all participants used time from injury to make return to sport decisions, while few participants reported using activity limitations with upper extremity physical performance tests when making return to sport decisions. Almost all participants stated that they tailored their battery of tests based on the sport to which the athlete is returning, and expressed the desire to use more physical performance tests in their return to sport assessments.

Results comparing responses reported by physical therapists with and without sports specialization in the criteria used with upper extremity athletes in return to sport decisions are shown in Figure 2. There were no significant differences (>0.05) in the use of time from injury or contextual factors. However, sports specialists reported greater use of quantitative evaluation of muscle performance with hand-held-dynamometry (70.5%) than non-specialists (50.3%) (p<0.001). Although commonly used by both groups, non-sports specialists also rely on more frequent use of manual muscle testing (<p<0.001) in return to sport decisions. Due to the low reported frequency of use isokinetic testing (<20%) overall, there were no significant differences between sports specialists than non-specialists. Most remarkably, sports specialists reported greater use of activity limitation assessments with physical performance tests. Specifically, 71.6% of sports specialists compared to less than 37% of non-sports specialists use the Closed Kinetic Chain Upper Extremity Stability Test. This was similar with the Upper Quarter Y-Balance Test that was used by 60.5% of sports-specialists compared to 36.0% of non-sports specialists (p<0.001). All the other physical performance tests were used infrequently (<28%) by sports specialists and non-sports specialists (<16%).

BARRIERS TO THE USE OF PHYSICAL PERFORMANCE TESTS

As shown in Table 3, reported barriers to the use of physical performance tests included a lack of time (44.2%) and equipment (51.8%), a perceived lack of evidence supporting the use of upper extremity physical performance tests (38.0%), and a clinician’s lack of understanding of available evidence (50.2%). Lack of patient interest (7.6%) and lack of referral source interest (19.5%) were less commonly cited barriers. There were a few differences between barriers reported by sports specialists and non-sports specialists. Sports specialists were more likely (p<0.001) to cite a perceived lack of evidence supporting the use of upper extremity physical performance tests compared to non-specialists (48.5% versus 34.1%) and less likely (p<0.001) to cite a lack of understanding of available evidence (26.9% versus 58.8%). No other differences in perceived barriers were found between sports specialist and non-specialist groups.

THE FREQUENCY OF USE OF PHYSICAL PERFORMANCE TESTS IN DISCHARGE/RETURN TO SPORT PLANNING

Overall, less than 25% of participants reported that their patients consistently passed all physical performance tests.
Table 2. Frequency (n and %) of criteria used in return to sports (RTS) decisions by International Classification of Function, Disability, and Health (ICF) framework

<table>
<thead>
<tr>
<th>ICF category</th>
<th>Frequency that Criteria is Used in RTS Decisions</th>
<th>All Respondents (n=498)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contextual Factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timeline from injury</td>
<td>487</td>
<td>97.8</td>
</tr>
<tr>
<td>Patient self-reported readiness</td>
<td>464</td>
<td>93.2</td>
</tr>
<tr>
<td>Patient reported outcome measures</td>
<td>403</td>
<td>80.9</td>
</tr>
<tr>
<td>Impairments, Body Structure, and Function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range of motion</td>
<td>491</td>
<td>98.6</td>
</tr>
<tr>
<td>Manual muscle testing</td>
<td>411</td>
<td>82.5</td>
</tr>
<tr>
<td>Hand-held dynamometry</td>
<td>277</td>
<td>55.6</td>
</tr>
<tr>
<td>Isokinetic testing</td>
<td>98</td>
<td>19.7</td>
</tr>
<tr>
<td>Proprioception</td>
<td>283</td>
<td>56.8</td>
</tr>
<tr>
<td>Activity Restrictions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seated Shot-Put Test</td>
<td>115</td>
<td>23.1</td>
</tr>
<tr>
<td>Closed Kinetic Chain Upper Extremity Stability Test</td>
<td>228</td>
<td>45.8</td>
</tr>
<tr>
<td>Upper Quarter Y-Balance Test</td>
<td>212</td>
<td>42.6</td>
</tr>
<tr>
<td>Timed Pushup Test</td>
<td>93</td>
<td>18.7</td>
</tr>
<tr>
<td>One Arm Hop Test</td>
<td>45</td>
<td>9.0</td>
</tr>
<tr>
<td>Athletic Shoulder Test</td>
<td>60</td>
<td>12.0</td>
</tr>
<tr>
<td>Shoulder Arm Return to Sport Test</td>
<td>54</td>
<td>10.8</td>
</tr>
</tbody>
</table>

*Figure 2. Comparison of information used in return to sport decisions between sports specialists (N=154) and non-specialists (N=364).  
*p<0.001

International Journal of Sports Physical Therapy
before discharge (Figure 3A). More than a third (36.6%) of sports specialists report patients consistently pass physical performance tests (Figure 3B) compared to less than a quarter (20.6%) of non-specialists (Figure 3C) (p=0.001).

The most cited reason participants report patients with return to sport goals being discharged prior to full physical performance was insurance visit limitation (68.9%), followed by patient self-discharge (67.9%), financial reasons (54.5%), clearance from another healthcare provider (52.8%), and external pressure for the athlete to return to sport (54.5%). Despite the infrequent use of physical performance tests, very few of the participants (2.2%) felt that physical performance tests were not important in discharge planning patients with return to sport goals, suggesting that most therapists believe physical performance tests should be used.

DISCUSSION

The overarching purpose of this study was to explore the reported frequency of physical performance testing in assessing return to sport readiness by physical therapists treating athletes with upper extremity injuries, and the perceived potential barriers that may limit the use of these tests. The hypothesis that the majority of participants do not use these tests was confirmed as fewer than half of participants reported using any physical performance test in making return to sport decisions for athletic patients with shoulder or elbow injuries. Similarly, the hypothesis that the greatest reported barriers to the use of physical performance tests would be a lack of understanding and awareness of current available literature was partially confirmed as lack of equipment was the most commonly reported barrier, followed by lack of understanding of the literature, lack of time, and perceived lack of literature supporting these tests. The secondary aim of this study was to compare practice patterns of clinicians with sports physical therapy specialty certification to clinicians without this certification. This hypothesis was confirmed as sports specialist clinicians were significantly more likely to use physical performance tests than non-specialist clinicians.

Table 3. Frequency of reported barriers to the use of physical performance tests

<table>
<thead>
<tr>
<th>Barrier</th>
<th>All Participants (n=498)</th>
<th>Sports Specialists (n=134)</th>
<th>Non-Specialists (n=364)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>%</td>
<td>n</td>
</tr>
<tr>
<td>Lack of time</td>
<td>220</td>
<td>44.2</td>
<td>56</td>
</tr>
<tr>
<td>Lack of equipment</td>
<td>258</td>
<td>51.8</td>
<td>67</td>
</tr>
<tr>
<td>Lack of understanding of literature supporting PPTs</td>
<td>250</td>
<td>50.2</td>
<td>36</td>
</tr>
<tr>
<td>Perceived lack of research supporting use of PPTs</td>
<td>189</td>
<td>38.0</td>
<td>65</td>
</tr>
<tr>
<td>Lack of referral source interest</td>
<td>97</td>
<td>19.5</td>
<td>29</td>
</tr>
<tr>
<td>Lack of patient interest</td>
<td>37</td>
<td>7.6</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 3. Reported frequency that patients pass all physical performance tests (PPTs) before discharge.

A. All Participants (n=498), B. Sports Specialists (n=134), and C. Non-Sports Specialists (n=364).
INFORMATION USED IN RETURN TO SPORT DECISIONS

A particularly striking finding was that fewer than half of all participants (45.2%) utilized any physical performance tests to determine if a patient was appropriate to be cleared for sport, thereby neglecting to assess an athlete's activity limitations. This percentage is even lower in non-specialist clinicians with only 36.2% of participants using physical performance tests compared to the 71.6% of sports specialist clinicians utilizing physical performance tests. This disparity may be partially explained by the advanced training sports specialists receive in return to sport assessment. However, in addition to assessing impairments, participation, and contextual factors, evaluating activity limitations is considered an entry-level skill by the American Physical Therapy Association (APTA) per their Guide to Physical Therapy Practice. The data suggests that, regardless of a clinician's sports specialization status, the physical therapy profession is overlooking a significant opportunity to assess activity limitations in this population.

One consideration is whether return to sport testing itself is an assessment that should be employed only with specialized training. The relative paucity of physical performance tests used in return to sport testing coupled with the reported lack of understanding of relevant evidence often results in a knee-jerk reaction to push physical performance tests into entry-level curriculum. However, it is important to first ask whether return to sport testing is truly an entry-level skill or that of an advanced practitioner. If it is the latter, this suggests the focus should not be on changing entry-level DPT curriculum but improving post-professional opportunities instead. For US-based specialists, the Description of Specialty Practice (DSP) for sports lists the implementation of "functional tests to determine athlete's ability and readiness to return to sports activities" and implementing "sport-specific criteria and recommendations regarding the athlete's readiness to return to sport" as activities performed by the board-certified specialist. The Description of Residency Practice (DRP) also notes that a residency program must utilize a curriculum that is inclusive of all the learning domains as noted in the Description of Specialty Practice, suggesting that the skills associated with return to sport decision-making are indeed better suited for residency-level education as opposed to entry-level, and that return to sport decisions are in line with specialty practice. Thus, in order to improve the utilization of physical performance tests in return to sport decision-making, barriers and challenges associated with accessing quality post-professional education should be explored.

BARRIERS TO THE USE OF PHYSICAL PERFORMANCE TESTS IN RETURN TO SPORT PLANNING

A final takeaway from these findings is the distinct need for guidance on the clinical use of upper extremity physical performance tests. There has long been a call for higher quality research on upper extremity physical performance tests in both the healthy and injured athletic population, and sports specialists who participated in this study echoed this call as nearly half responded that a perceived lack of quality evidence is a significant barrier to their use of physical performance tests. However, the most cited barriers for the use of physical performance tests for upper extremity injuries from all participants were a lack of understanding of the current research, a lack of time, and a lack of equipment. These barriers are intricately linked, as a large percentage of physical performance tests currently available require minimal time and equipment to perform. With new literature providing guidance on how to utilize existing physical performance tests, each of these barriers can be considerably lessened. Considering these responses, the authors believe that the need for literature providing guidance on the use of upper extremity physical performance tests may be greater than the need for literature validating their use.

This study is not without limitations. First, while the study was distributed through the mailing lists of several professional organizations, it was also shared via social media limiting the ability to calculate an overall response rate. Second, in distributing through the mailing list of sports rehabilitation-specific organizations, there may have been somewhat of a selection bias as this clinician population may be more inclined to use physical performance tests than clinicians that do not belong to these sports rehabilitation organizations. That said, based on the current data comparing sports specialists to non-specialist clinicians, it is very possible that including a greater population of non-specialist clinicians would result in an even lower percentage of individuals reporting the use of upper extremity physical performance tests. Finally, while the survey was distributed internationally, most participants were US clinicians. As a result, these practice patterns may be generalized to physical therapist practice within the United States, but not necessarily indicative of practice patterns globally.

CONCLUSION

The results of this survey suggest that the vast majority of clinicians are not using physical performance tests in making return to sport decisions for athletes with upper extremity injuries. By omitting these tests, and neglecting to assess an athlete's activity limitations, physical therapists are "missing the forest for the trees" and may be returning athletes to sport before full physical performance. While sports specialist clinicians are more likely to utilize these tests to assess an athlete's activity limitations, all participants highlighted a perceived lack of supporting research, a lack of understanding of current research, and a lack of time and equipment to perform these tests in the clinic. Strategies recommended to overcome these barriers include increasing the emphasis on assessing activity limitations for return to sport clinical decision making in entry-level and post-professional education, reducing the barriers and challenges associated with accessing post-professional education, and developing clinical guidelines for the utilization of physical performance tests in athletes with upper extremity injuries.

Missing The Forest For The Trees: A Lack Of Upper Extremity Physical Performance Testing In Sports Physical Therapy

International Journal of Sports Physical Therapy
CONFLICTS OF INTEREST

Authors have no reported conflicts of interest.

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REFERENCES


SUPPLEMENTARY MATERIALS

Appendix
Diagnostic Imaging for Distal Extremity Injuries in Direct Access Physical Therapy: An Observational Study

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Keywords: physical therapy, direct-access, fracture.

Background
Military physical therapists practicing direct-access routinely utilize diagnostic imaging and numerous published case reports demonstrate the ability of physical therapists to diagnose and appropriately disposition patients with foot/ankle and wrist/hand fractures. However, no larger cohort studies have explored the utilization of diagnostic imaging by physical therapists to detect fractures.

Hypothesis/Purpose
To describe the utilization of diagnostic imaging in foot/ankle and wrist/hand injuries by physical therapists in a direct-access sports physical therapy clinic.

Study Design
Retrospective cohort study.

Methods
The Agfa Impax Client 6 image viewing software (IMPAX) was searched from 2014 to 2018 for patients with diagnostic imaging ordered for foot/ankle and wrist/hand injuries. The Armed Forces Health Longitudinal Technology Application (AHLTA) electronic medical record was independently reviewed by the principal and co-investigator physical therapists. Data extracted were demographics and elements from the patient history and physical examination.

Results
In foot/ankle injuries, physical therapists diagnosed a fracture in 16% of the 177 cases and waited for an average of 3.9 days and 1.3 visits before ordering imaging. In wrist/hand injuries, physical therapists diagnosed a fracture in 24% of the 178 cases and waited for an average of 3.7 days and 1.2 visits before ordering imaging. The time to definitive care from the initial physical therapy evaluation was significantly different (p = 0.04) for foot/ankle fractures (0.6 days) compared to wrist/hand fractures (5.0 days). The Ottawa Ankle Rules demonstrated a negative likelihood ratio (-LR) of 0.11 (0.02, 0.72) and a positive likelihood ratio (+LR) of 1.99 (1.62, 2.44) for the diagnosis of foot/ankle fracture.

Conclusions
Physical therapists utilizing diagnostic imaging in a direct-access sports physical therapy clinic diagnosed fractures in similar proportions for foot/ankle and wrist/hand injuries and quickly dispositioned patients to definitive care for those fractures. The diagnostic accuracy of the Ottawa Ankle Rules was similar to previously reported values.
Level of Evidence

Level 3.

INTRODUCTION

Musculoskeletal injuries are the leading cause of disability worldwide, affecting approximately 1.7 billion people. In the United States, musculoskeletal injuries affect one in two Americans, resulting in 62.7 million medical visits and $53.1 billion in direct treatment costs. The annual cost for treatment and lost wages is a staggering $980 billion. In addition to monetary cost, musculoskeletal injuries limit mobility, leading to early retirement, reduced well-being, and reduced societal participation.

Participation in athletic activities produces a substantial number of injuries. Each year, 4.2 million sports injuries require medical attention; 61% of these injuries involve the musculoskeletal system. In collegiate athletics, the overall rate of injury is estimated to be 13.8 per 1000 exposures. Of all severe injuries, 14.4% were fractures. Severe injuries to the foot/ankle and wrist/hand are common. In NCAA football, foot/ankle injuries occur at a rate of 1.5 per 1000 exposures, with the most common being fractures of the metatarsal (0.03 per 1000 exposures), malleolus (0.02 per 1000 exposures), and phalanx (0.01 per 1000 exposures). When examining differences in ankle injuries between athletic settings, fractures account for 3.8% of high school injuries but only 0.8% of collegiate injuries. The rate of wrist/hand injuries in all NCAA sports is 0.5 per 1000 exposures, with the most common being metacarpal fractures (0.51 per 1000 exposures) and phalangeal fractures (0.5 per 1000 exposures).

In the military, 50% of Army soldiers sustain a new injury annually. These injuries contribute to over one million medical encounters and over 10 million limited duty days per year. In a two-month study of 1,475 Soldiers across a variety of units, medical care associated with the treatment of musculoskeletal injuries exceeded $1.3 million ($1.9K per injury). Among 417 Marine Corps recruits, over 50% sustained a musculoskeletal injury during the 11 or 12-week training period.

Physical therapists practicing direct-access care in the military routinely utilize diagnostic imaging within their differential diagnosis and clinical reasoning processes. This model of early access to physical therapy reduces unnecessary imaging and healthcare costs and improves outcomes. Two recent studies of diagnostic imaging in physical therapy demonstrated that physical therapists order imaging appropriately, with 83-91% of cases judged to be appropriate according to the American College of Radiology (ACR) Criteria. Physical therapists also utilize imaging safely; no adverse events were reported in over 1,000 imaging studies in a recent study examining the practice of military physical therapists. When comparing physical therapists to primary care providers using data from a nationally standardized healthcare performance measure, physical therapists were more likely to adhere to low back pain imaging guidelines in young, athletic patients.

Physical therapists have demonstrated the ability to identify fractures when operating in a direct-access setting. Numerous case reports from a direct-access sports physical therapy clinic have been published that highlight the ability of physical therapists to appropriately recognize and disposition patients with foot/ankle and wrist/hand fractures. Among non-military physical therapists who are not currently able to refer patients directly to a radiologist, 55 to 95% reported routinely performing the nine fundamental skills in their clinical practice that are necessary to utilize diagnostic imaging effectively. The Ottawa Ankle Rules are a valid screening tool for foot/ankle fractures but have not been studied in a physical therapy direct-access setting.

To the authors’ knowledge, no published cohort studies have explored the utilization of diagnostic imaging to detect fractures by physical therapists in a direct-access practice setting. The purpose of this study was to describe the utilization of diagnostic imaging in acute foot/ankle and wrist/hand injuries by physical therapists in a direct-access sports physical therapy clinic. Based on clinical experience and observations, it was hypothesized that: 1. upper extremity imaging would result in a significantly greater proportion of confirmed fracture diagnoses than lower extremity imaging; 2. the average time from initial evaluation to definitive care for patients evaluated by physical therapists and diagnosed with a fracture would be less than five days; 3. the Ottawa Ankle Rules would perform similarly in a direct-access physical therapy setting as in an emergency department; 4. no individual examination item would result in clinically meaningful diagnostic accuracy for the diagnosis of wrist/hand or foot/ankle fractures.

METHODS

This was a retrospective cohort study conducted at Keller Army Community Hospital (KACH) at the United States Military Academy (USMA) at West Point. The Arvin Cadet Physical Therapy Clinic is a direct-access clinic where nearly all USMA Cadets with musculoskeletal injuries and/or pain are evaluated and treated. All physical therapists possess clinical privileges with the ability to order diagnostic imaging and prescribe a limited number of medications, including non-steroidal anti-inflammatory medications (NSAIDs) and non-opioid analgesics. The Naval Medical Center – Portsmouth Institutional Review Board
approved the research design and protocol before data collection. The Agfa Impax Client 6 (Agfa Healthcare) image viewing software program (IMPAX) was searched with a location code for the Arvin Physical Therapy Clinic from June 2014 to June 2018 for patients with diagnostic imaging ordered for foot/ankle and wrist/hand injuries. More recent records were not utilized due to a nomenclature change that prevented an accurate search for the specific body regions of interest. For each patient identified, the Armed Forces Health Longitudinal Technology Application (AHLTA) electronic medical records (EMR) were independently reviewed by the principal and co-investigator physical therapists. All reviewing physical therapists held board certification in orthopaedic or sports physical therapy. Documentation from physical therapy encounters and radiology exams was extracted and de-identified. Demographic data included patient age and sex, duration of symptoms, and location of symptoms. If a provider’s note did not explicitly state the duration of symptoms in days/weeks/months, seven days was input for acute symptoms, 30 days for subacute symptoms, and 90 days for chronic symptoms. Table 1 shows specific variables of interest for foot/ankle and wrist/hand injury data extraction, which were identified based on the clinical experience of the authors practicing in this setting. The status on the Ottawa Ankle Rules was recorded for all foot and ankle injuries. When an element of the patient history or physical examination was not reported in the patient note, it was coded as a “negative” finding. Variables of interest for all injuries included: (1) diagnosis of a fracture, (2) number of physical therapy visits before the imaging order, (3) amount of time from initial physical therapy evaluation to the imaging order, and (4) amount of time from initial physical therapy evaluation to definitive care. As treatment of fractures is beyond the scope of physical therapist practice, the time to definitive care was defined as when an orthopaedic surgeon or orthopaedic physician’s assistant was consulted on the patient’s case, either by the physical therapist via telephone or by the patient in person.

Statistical analyses were performed in Microsoft Excel 365 (Microsoft, Inc) and SPSS version 28.0 (IBM Corp) with α = 0.05 set a priori for all analyses. Descriptive statistics were calculated for demographics, the number of imaging orders resulting in fracture, the time between the initial evaluation and the imaging order, and the time from the initial evaluation to definitive care for fractures. Homogeneity of the data was assessed using Levene’s test and all data were assessed for normal distribution using a Shapiro-Wilk test. Skewness and kurtosis were also calculated to assess for normal distribution. The nonparametric Mann-Whitney U test examined differences in time to imaging, visits to imaging, and time from physical therapy evaluation to definitive care between upper and lower extremity injuries, as these data were not normally distributed and had unequal variances. A Chi-square test was used to compare the proportion of fractures identified with upper versus lower extremity imaging orders. The diagnostic accuracy of items from the patient history and physical exam, including the Ottawa Ankle Rules, was examined by calculating sensitivity, specificity, and likelihood ratios with 95% confidence intervals using the PDro Confidence Interval Calculator (Herbert R. Confidence Interval Calculator (2013). [https://pedro.org.au/english/resources/confidence-interval-calculator/].

RESULTS

From June 2014 to June 2018 with a location code for the Arvin Physical Therapy Clinic, there were 267 imaging orders for foot/ankle injuries and 254 imaging orders for wrist/hand injuries (Figure 1). Because the search was filtered by location and not ordering provider, records were returned that were not ordered by a physical therapist. The final analysis included 177 cases of foot/ankle injuries and 178 cases of wrist/hand injuries ordered by 15 physical therapists. There were 90 cases of foot/ankle injuries and 76 cases of wrist/hand injuries excluded when the imaging was ordered by other medical providers. Demographics are shown in Table 2.

Table 3 shows the cases diagnosed as fractures, the time visits to imaging from the initial physical therapy evaluation, and the time to definitive care for diagnosed fractures. Fractures were noted in the radiology report for 16% of the foot/ankle cases and 24% of the wrist/hand cases. There were no significant differences between foot/ankle and wrist/hand injuries for the percentage of imaging orders diagnosed with a fracture or the time in days/visits from initial evaluation to imaging. The physical therapist waited for an average of 3.9 days and 1.3 visits before ordering imaging for foot/ankle injuries and 3.7 days and 1.2 visits for wrist/hand injuries. The time to definitive care from the initial physical therapy evaluation was significantly different (p = 0.04) for foot/ankle fractures (0.6 days) compared to wrist/hand fractures (5.0 days).

The diagnostic accuracy of the Ottawa Ankle Rules in screening for fractures is shown in Figure 2, with a negative likelihood ratio (-LR) of 0.11 (0.02, 0.72) and positive likelihood ratio (+LR) of 1.99 (1.62, 2.44). The diagnostic accuracy of other elements of the patient history and physical examination are shown in Table 4; no individual element of the examination demonstrated acceptable diagnostic accuracy to either rule out or rule in fractures in foot and ankle or wrist and hand injuries.

DISCUSSION

The purpose of this study was to describe the utilization of diagnostic imaging in acute foot/ankle and wrist/hand injuries by physical therapists in a direct-access sports physical therapy clinic. Orders for radiographs resulted in the diagnosis of a fracture in 16% of foot/ankle cases and 24% of wrist/hand cases. The results partially confirmed the hypotheses. For screening for fracture, the diagnostic accuracy of the Ottawa Ankle Rules was similar in this direct-access physical therapy setting as was previously reported in emergency departments. No individual examination item had a clinically meaningful likelihood ratio for the diagnosis of foot/ankle or wrist/hand fractures. The average time
Table 1. Variables of interest were extracted from the patient history and physical examination within the patient care notes.

<table>
<thead>
<tr>
<th>Patient History</th>
<th>Foot/Ankle</th>
<th>Wrist/Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient self-reported outcomes</td>
<td>SANE, NPRS</td>
<td>SANE, NPRS</td>
</tr>
<tr>
<td>Injury description/MOI</td>
<td>Able to continue activity? (+) pop at time of injury?</td>
<td>Able to continue activity? (+) pop at time of injury?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Examination</th>
<th>Foot/Ankle</th>
<th>Wrist/Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>Swelling? Ecchymosis?</td>
<td>Swelling? Ecchymosis?</td>
</tr>
<tr>
<td>Palpation</td>
<td>Location of tenderness</td>
<td>Location of tenderness</td>
</tr>
<tr>
<td>Limited range of motion</td>
<td>Ankle dorsiflexion</td>
<td>Wrist flexion</td>
</tr>
<tr>
<td></td>
<td>Ankle plantarflexion</td>
<td>Wrist extension</td>
</tr>
<tr>
<td></td>
<td>Ankle inversion</td>
<td>Wrist ulnar deviation</td>
</tr>
<tr>
<td></td>
<td>Ankle eversion</td>
<td>Wrist radial deviation</td>
</tr>
<tr>
<td></td>
<td>Limited range of motion</td>
<td>Forearm pronation</td>
</tr>
<tr>
<td></td>
<td>Anterior drawer</td>
<td>Forearm supination</td>
</tr>
<tr>
<td></td>
<td>Talar tilt</td>
<td>Scaphoid shift</td>
</tr>
<tr>
<td></td>
<td>External rotation stress</td>
<td>1st MCP varus/valgus</td>
</tr>
<tr>
<td></td>
<td>Squeeze test</td>
<td>IP varus/valgus</td>
</tr>
</tbody>
</table>

Abbreviations: SANE, Single Assessment Numerical Evaluation; NPRS, Numerical Pain Rating Scale; MOI, mechanism of injury; MCP, metacarpophalangeal.

Table 2. Demographics for Patients with Foot/Ankle and Wrist/Hand Radiographs from June 2014 to June 2018.

<table>
<thead>
<tr>
<th>Foot &amp; Ankle (n=177)</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>20.2 (2.0)</td>
</tr>
<tr>
<td>Sex (female)</td>
<td>22.6% (40)</td>
</tr>
<tr>
<td>Body Region</td>
<td>% (n)</td>
</tr>
<tr>
<td>Tibia</td>
<td>0.6% (1)</td>
</tr>
<tr>
<td>Ankle</td>
<td>52.0% (92)</td>
</tr>
<tr>
<td>Foot</td>
<td>44.6% (79)</td>
</tr>
<tr>
<td>Toe</td>
<td>2.8% (5)</td>
</tr>
<tr>
<td>Duration of Symptoms (days)</td>
<td>10.1 (22.9)</td>
</tr>
<tr>
<td>Acute</td>
<td>82.5% (146)</td>
</tr>
<tr>
<td>Subacute</td>
<td>13.6% (24)</td>
</tr>
<tr>
<td>Chronic</td>
<td>4.0% (7)</td>
</tr>
<tr>
<td>Wrist &amp; Hand (n=178)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>20.5 (1.9)</td>
</tr>
<tr>
<td>Sex (female)</td>
<td>19.7% (35)</td>
</tr>
<tr>
<td>Body Region</td>
<td>% (n)</td>
</tr>
<tr>
<td>Wrist</td>
<td>55.1% (98)</td>
</tr>
<tr>
<td>Hand</td>
<td>28.1% (50)</td>
</tr>
<tr>
<td>Finger</td>
<td>16.9% (30)</td>
</tr>
<tr>
<td>Duration of Symptoms (days)</td>
<td>18.9 (51.4)</td>
</tr>
<tr>
<td>Acute</td>
<td>76.4% (136)</td>
</tr>
<tr>
<td>Subacute</td>
<td>18.5% (33)</td>
</tr>
<tr>
<td>Chronic</td>
<td>5.1% (9)</td>
</tr>
</tbody>
</table>

Abbreviations: SD, standard deviation.

Figure 1. Flow diagram of included and excluded cases. Abbreviations: ER, emergency room.

from the initial physical therapy evaluation to definitive care was less than five days for foot/ankle fractures, but equal to five days for wrist/hand fractures. There were no significant differences in the rate of imaging that resulted in the diagnosis of foot/ankle or wrist/hand fractures. This is the first study to describe how physical therapists working in a direct-access setting utilize diagnostic imaging to diagnose fractures.

The Ottawa Ankle Rules performed similarly in this sample of young, athletic patients evaluated by physical therapists without physician referral compared to patients evalu-
Table 3. Diagnosis of Fractures and Practice Patterns.

<table>
<thead>
<tr>
<th>Diagnosis of Fracture (+)</th>
<th>Foot &amp; Ankle (n=177) Mean (SD); % (n)</th>
<th>Wrist &amp; Hand (n=178) Mean (SD); % (n)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis of Fracture (+)</td>
<td>16% (29)</td>
<td>24% (42)</td>
<td>0.09</td>
</tr>
<tr>
<td>Time from Evaluation to Imaging (days)</td>
<td>3.9 (12.2)</td>
<td>3.7 (10.2)</td>
<td>0.18</td>
</tr>
<tr>
<td>Time from Evaluation to Imaging (visits)</td>
<td>1.3 (0.8)</td>
<td>1.2 (0.6)</td>
<td>0.11</td>
</tr>
<tr>
<td>Time from Evaluation to Definitive Care (days)</td>
<td>0.6 (3.5)</td>
<td>5.0 (16.6)</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Figure 2. Diagnostic Test Properties of Ottawa Ankle Rules.

<table>
<thead>
<tr>
<th>Ottawa Ankle Rules (+)</th>
<th>Fracture</th>
<th>No Fracture</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa Ankle Rules (+)</td>
<td>17</td>
<td>69</td>
<td>86</td>
</tr>
<tr>
<td>Ottawa Ankle Rules (-)</td>
<td>1</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>Ottawa Rules N/A</td>
<td>11</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>148</td>
<td>177</td>
</tr>
</tbody>
</table>

Sn = 0.94 (0.74, 0.99); Sp = 0.52 (0.44, 0.60)
+LR = 1.99 (1.62, 2.44); -LR = 0.11 (0.02, 0.72)

Table 4. Diagnostic Test Properties for Elements of the Patient History and Physical Examination.

<table>
<thead>
<tr>
<th></th>
<th>Sn</th>
<th>Sp</th>
<th>+LR</th>
<th>-LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot &amp; Ankle (n=177)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Able to bear weight</td>
<td>0.90</td>
<td>0.18</td>
<td>1.09</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>(0.74,0.96)</td>
<td>(0.12,0.25)</td>
<td>(0.94,1.26)</td>
<td>(0.19,1.82)</td>
</tr>
<tr>
<td>Able to continue activity</td>
<td>0.45</td>
<td>0.53</td>
<td>0.96</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>(0.28,0.62)</td>
<td>(0.45,0.61)</td>
<td>(0.62,1.49)</td>
<td>(0.42,2.07)</td>
</tr>
<tr>
<td>(+) Report of &quot;pop&quot;</td>
<td>0.10</td>
<td>0.89</td>
<td>0.96</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>(0.04,0.26)</td>
<td>(0.83,0.92)</td>
<td>(0.30,0.37)</td>
<td>(0.88,1.15)</td>
</tr>
<tr>
<td>(+) Swelling</td>
<td>0.59</td>
<td>0.35</td>
<td>0.90</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>(0.41,0.74)</td>
<td>(0.28,0.43)</td>
<td>(0.65,1.26)</td>
<td>(0.73,1.91)</td>
</tr>
<tr>
<td>(+) Ecchymosis</td>
<td>0.24</td>
<td>0.79</td>
<td>1.15</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>(0.12,0.42)</td>
<td>(0.71,0.84)</td>
<td>(0.56,2.36)</td>
<td>(0.77,1.20)</td>
</tr>
<tr>
<td>(+) Tenderness to palpation</td>
<td>1.00</td>
<td>0.03</td>
<td>1.03</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>(0.83,1.00)</td>
<td>(0.01,0.07)</td>
<td>(1.00,1.06)</td>
<td>---</td>
</tr>
<tr>
<td>Wrist &amp; Hand (n=178)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Able to continue activity</td>
<td>0.38</td>
<td>0.62</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>(0.25,0.52)</td>
<td>(0.53,0.70)</td>
<td>(0.64,1.55)</td>
<td>(0.76,1.32)</td>
</tr>
<tr>
<td>(+) Report of &quot;pop&quot;</td>
<td>0.07</td>
<td>0.96</td>
<td>1.62</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>(0.02,0.19)</td>
<td>(0.91,0.98)</td>
<td>(0.42,6.20)</td>
<td>(0.89,1.06)</td>
</tr>
<tr>
<td>(+) Swelling</td>
<td>0.60</td>
<td>0.52</td>
<td>1.25</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>(0.44,0.73)</td>
<td>(0.44,0.60)</td>
<td>(0.92,1.69)</td>
<td>(0.52,1.16)</td>
</tr>
<tr>
<td>(+) Ecchymosis</td>
<td>0.26</td>
<td>0.86</td>
<td>1.88</td>
<td>0.86</td>
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<td></td>
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<td>1.35</td>
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<td></td>
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<td>(0.05,0.15)</td>
<td>(0.85,1.09)</td>
<td>(0.50,3.61)</td>
</tr>
</tbody>
</table>

When the element was not reported in the patient note, it was coded as a "negative" finding.

uated in an emergency department by emergency medicine physicians and a previous study of similar patients evaluated by orthopaedic surgeons and physical therapists. The Ottawa Ankle Rules were designed to be a screening test, where the -LR is the statistic of most interest. In a 2005 systematic review, the -LR was 0.06 (0.02, 0.19) when applied at less than 48 hours from injury and 0.11 (0.07, 0.18) when applied greater than 48 hours from injury. In a similar population as this study, the Sn of the Ottawa Ankle Rules when used by both orthopaedic surgeons and physical therapists was 1.0 (0.95, 1.0) (because there were no false negative tests, a -LR was unable to be calculated). In this study, the -LR was 0.11 (95% CI 0.02, 0.72), with a very large proportion of acute foot/ankle injuries (82.5%, mean dura-
tion of symptoms 10.1 days), equal to the value reported by Bachman et al at greater 48 hours from injury.

Although the time from the initial physical therapy evaluation to definitive treatment was significantly different for foot/ankle and wrist/hand fractures, it was less than one week in both regions. On average, those with foot/ankle fractures were definitively treated within 24 hours, while those with wrist/hand fractures were definitively treated in less than one week. According to the American College of Radiology (ACR) Appropriateness Criteria for acute ankle pain, the current clinical imaging guidelines to determine if radiographs are necessary are the Ottawa Ankle Rules.\textsuperscript{36} For the initial imaging of suspected acute hand and wrist trauma, the ACR Appropriateness Criteria state that radiography is always indicated.\textsuperscript{37} It was not feasible to determine the proportion of patients that had imaging ordered and the ACR Appropriateness Criteria recommendations for radiographs are more clear for acute foot/ankle injuries than acute wrist/hand injuries. Differences between the two regions may be due to the absence of clinical decision rules in the upper extremity and/or the need for repeat radiographs to effectively rule out fractures in the early stages (i.e., scaphoid).

Fractures were diagnosed by physical therapists in 1.6 out of every ten foot/ankle radiographs and 2.4 out of every ten wrist/hand radiographs. While radiographs are often ordered to rule out fractures, this means that physical therapists "hit the target" more frequently when ordering wrist/hand radiographs. Keil et al retrospectively analyzed 108 diagnostic imaging referrals by civilian physical therapists practicing in a direct-access setting.\textsuperscript{17} Among 15 orders for foot/ankle or wrist/hand radiographs, they reported seven fractures, which equates to 54% of all radiographs. The difference in the proportion of radiograph orders that resulted in a fracture diagnosis may have been due to differences in the patient populations, although the demographics of the patients were not reported in the Keil et al study.

There are several limitations to this study. The patients whose cases were reviewed were all young, physically active Cadets at a single military medical facility, which may limit generalizability to other populations and age groups. This was a retrospective study. While the patient notes for each case were thoroughly reviewed, providers may have made verbal recommendations or failed to document information that was not reflected in the electronic medical record. Specifically, when an element of the patient history or physical exam was missing (i.e., ability to continue play, etc.), we coded that element as negative. While many military physical therapists do not document all negative findings, this may have affected the calculation of diagnostic accuracy. Five board-certified physical therapists reviewed imaging orders and extracted results from the official radiologist’s report, which is a potential source of bias for the observational results. The physical therapists reviewing the cases had to make judgments on the presence or absence of elements of the examination when there was missing or incomplete information. The only cases of foot/ankle and wrist/hand injuries studied were those referred for diagnostic imaging and do not represent the entire sample of patients with injuries to those regions, thus creating selection bias in the calculation of diagnostic accuracy.

CONCLUSION

Physical therapists utilizing diagnostic imaging in a direct-access sports physical therapy clinic diagnosed fractures when ordering radiographs in 16% of foot/ankle cases and 24% of wrist/hand cases. The diagnostic accuracy of the Ottawa Ankle Rules was similar to previously reported values and no individual examination item was able to assist in fracture diagnosis. The average time from the initial physical therapy evaluation to definitive care was short in both foot/ankle and wrist/hand fractures. Future research should utilize larger data sets available in both civilian and military electronic medical record systems to explore the impact of direct-access physical therapy on fracture management and identify clusters of tests that may assist in the diagnosis of various wrist/hand and foot/ankle fractures.

DISCLAIMER

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the United States Army or Department of Defense.

ETHICS APPROVAL

Study was approved by the Naval Medical Center Portsmouth Institutional Review Board (RHC-A-20-051).

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REFERENCES


Self-Movement Screening using the Symmio Application is Reliable and Valid for Identifying Musculoskeletal Risk Factors

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Keywords: Movement systems, reliability, self-screen, validity

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Background
Musculoskeletal health problems are one of the greatest healthcare expenses in the United States but patient-driven screening procedures to detect risk factors do not exist.

Hypothesis/Purpose
The purpose was to establish the inter-rater reliability of the Symmio Self-Screen application in untrained individuals and to investigate its accuracy to detect MSK risk factors such as pain with movement, movement dysfunction, and decreased dynamic balance.

Study Design
Cross-Sectional

Methods
Eighty (42 male, 38 female) healthy individuals mean age 26.5 ± 9.4 participated in the study. The inter-rater reliability of Symmio application was established by comparing self-screen scores from untrained subjects with the results simultaneously determined by a trained healthcare provider. Each subject was evaluated for pain with movement, movement dysfunction, and deficits in dynamic balance by two trained evaluators who were blinded to the Symmio results. The validity of Symmio was determined by comparing self-screen performance dichotomized as pass or fail with the reference standard of pain with movement, failure on the Functional Movement Screen™, and asymmetry on the Y Balance Test-Lower Quarter™ using three separate 2x2 contingency tables.

Results
The mean Cohen’s kappa coefficient was 0.68 (95% CI, 0.47–0.87) and the absolute agreement was 89% between self-assessment of subjects and the observation of a trained healthcare provider. There were significant associations for the presence of pain with movement (p=0.005), movement dysfunction (p=0.001), and dynamic balance deficits (p=0.005) relative to poor Symmio performance. The accuracy of Symmio to identify pain with movement, movement dysfunction, and dynamic balance deficits were 0.74 (95% CI, 0.63–0.85), 0.73 (95% CI, 0.62–0.82), and 0.69 (95% CI, 0.57–0.79), respectively.

Conclusions
The Symmio Self-Screen application is a reliable and feasible screening tool that can be used to identify MSK risk factors.
Level of Evidence
Level 2

INTRODUCTION

Musculoskeletal (MSK) health problems are one of the greatest healthcare expenses in the United States.\(^1\) Poor MSK health can cause significant loss of time from work and recreational activities, and it is strongly correlated with the development of chronic pain syndrome and opioid use.\(^2\) According to data from the World Health Organization, MSK health problems are second only to mental health disorders as the primary contributor to years of life with disability and 19\(^{th}\) in years of life lost across the globe.\(^3\) Over a 15-year period, the total number of years living with disability due to MSK conditions has increased from 77 million to 103 million and years of life loss have risen by more than 40 percent.\(^3\) Consequently, the economic and functional burden of MSK disorders will continue to increase as the general population becomes older due to longer life expectancies.\(^4\)

The risk of sustaining an MSK injury is increased by the presence of modifiable risk factors that can be assessed by a trained healthcare professional.\(^5\)-\(^8\) The Functional Movement Screen (FMS\(^{TM}\)) and Y Balance Test-Lower Quarter (YBT-LQ\(^{TM}\)) are reliable, movement-based tests that have a relationship to heightened injury risk when deficits are identified.\(^9\)-\(^12\) When multiple risk factors are considered using an evidence-based injury risk prediction algorithm, individuals identified as high-risk were 3.4 times more likely to sustain a non-contact MSK injury.\(^13\) Additionally, the more risk factors an individual possesses the more likely an MSK injury that limits participation in physical activity is to occur.\(^7\) Early identification of the development of risk factors or declining physical function could allow patients to take a more active role in preventive strategies,\(^14\) which researchers have shown can decrease the financial burden on both the individual and the healthcare system.\(^15\),\(^16\)

Patient-driven screening is widespread in its application among other healthcare specialties to create awareness of potential risk factors or conditions. Multiple body systems such as the cardiovascular, integumentary, endocrine, and lymphatic systems have patient-driven screens for early detection and subsequent intervention recommendations. The health of the cardiovascular system can be screened with a sphygmomanometer for blood pressure measurements, which is reliable in identifying possible cardiovascular disease.\(^17\) The use of educational materials and skin self-examinations allows for early detection and proper treatment of melanoma\(^18,19\) and breast cancer which has significantly increased survival rates.\(^20,21\) Glucometers have been useful in helping those with a diagnosis of diabetes to monitor the impact of medication and lifestyle factors on blood sugar levels.\(^22,23\) However, self-screening options for the MSK system are limited despite the growing need to combat rising disability and attenuating quality of life associated with poor MSK health. The increasing prevalence of MSK disorders warrants a user-friendly self-screening tool that can be administrated by the general public to aid in creating awareness of physical risk factors.

To date, there are no studies that have explored a patient-driven self-screening tool to reliably identify MSK risk factors. The Symmio Self-Screen (Symmio) is a downloadable application developed to be a user-friendly and cost-effective tool for the early identification of physical risk factors that may lead to MSK injuries. The primary purpose of this study was to establish the inter-rater reliability of the Symmio application in untrained individuals. It was hypothesized that Symmio will demonstrate moderate inter-rater reliability with a Cohen’s kappa value >0.40 when administered by untrained individuals. The secondary purpose of this study was to investigate the accuracy of Symmio to detect MSK risk factors such as pain with movement, movement dysfunction, and decreased dynamic balance. It was hypothesized that poor performance on Symmio would increase the odds of having pain with movement, dysfunctional movement quality on the FMS\(^{TM}\), and deficient dynamic balance on the YBT-LQ\(^{TM}\).

MATERIALS AND METHODS

STUDY DESIGN

A prospective cross-sectional design was used to establish the inter-rater reliability and discriminant validity of Symmio to identify the presence of painful or dysfunctional movement and dynamic balance deficits among a cohort of active individuals. The Standards for Reporting Diagnostic Accuracy Studies (STARD) statement for a diagnostic accuracy study design was followed for standardized reporting.\(^24\) Approval was granted from the institutional review board at the University of Evansville and informed consent forms were obtained before data collection.

PARTICIPANTS

A minimum sample size of 50 participants was needed to achieve a Cohen’s kappa value of 0.40 with an alpha of 0.05 and 80% power for a two-tailed test. To detect a sensitivity of 0.90, at least 58 participants would be required considering a prevalence of 0.60 and a 0.10 confidence interval width allowance.\(^25\) Anticipating 10% of the participants enrolled may have incomplete data, the final planned minimum target sample size was 64 participants.

A convenience sample of 80 individuals between the ages of 18 and 70 of either sex was enrolled in the study. Participants were excluded from enrollment in the study for lower-extremity amputation, vestibular disorder, lack of medical clearance for participation, current treatment for the inner ear, sinus or upper respiratory infection or head cold, cerebral concussion within the past three months, or inability to read or comprehend English.
PROCEDURES

Physical testing occurred during a single session with no follow-up required. After informed consent was obtained, the participants completed a demographic and medical history questionnaire and then completed Symmio, FMS™, and YBT-LQ™ testing. The order of physical testing was randomized to control for fatigue and changes in movement quality. All testers were blinded to the results of the tests.

The Symmio Self-Screen is a movement-based screening tool intended to identify MSK disorders using an instructional application on a smart phone or tablet. Symmio consists of five tests with two levels of difficulty for each movement including, 1) tandem toe touch, 2) shoulder mobility, 3) rotation, 4) deep squat, and 5) balance and reach (Figure 1). Participants were allowed three attempts to perform each movement and each test was scored as pass or fail per the criteria below on both right and left sides when applicable. Subjective report of pain with movement was recorded for each movement.

1. **Tandem Toe Touch**: While standing with feet in tandem stance, the participants were instructed to reach down and attempt to touch the toes of their forward foot while maintaining knee extension (Level 1). The test was repeated on the opposite side. The participants then attempted a more challenging test by repeating the movement but now attempting to touch the toes of their back foot (Level 2). Inability to touch the toes of the front foot on both sides at the Level 1 standard was considered failure.

2. **Shoulder Mobility**: The participants stood with feet together holding a horizontally folded standard piece of paper (8.5 x 11 in) in one hand. In one smooth motion, the participants simultaneously reached one hand behind their head (in a flexed and externally rotated position), and the other hand behind and up their back (in an extended and internally rotated position) attempting to pass the paper from one hand to the other (Level 1). The test was repeated on the opposite side. The participants then performed the test without the folded paper, attempting to touch their fingertips together (Level 2). Inability to pass the folded paper between hands on both sides at the Level 1 standard was considered failure.

3. **Deep Squat**: The participants stood with their feet together, shoulders flexed to 90°, and fingers extended. Maintaining the heels in contact with the ground, the participants descended into a deep squat and attempted to touch their fingertips to the ground within their footprint (Level 1). The participants then attempted a more challenging test by repeating the movement but with their fists closed (Level 2). Inability to touch the fingertips to the ground at the Level 1 standard was considered failure.

4. **Rotation**: The participants stood with feet together and shoulders flexed to 90° with fingers interlocked. Maintaining tall posture, the participants attempted to rotate their trunk and hips greater than 90° using their arms as a gauge (Level 1). The test was repeated on the opposite side. The participants then attempted a more challenging test by positioning their feet in tandem stance and repeating the rotation toward the forward leg (Level 2). Inability to rotate greater than 90° with feet together at the Level 1 standard on both sides was considered failure.

5. **Balance and Reach**: The participants stood two shoe lengths away from a wall, and while maintaining single leg balance on one foot with the heel down, the participants reached with the opposite foot to attempt to touch the point on the wall just above the ground five consecutive times without the foot touching down or losing balance (Level 1). The test was repeated on the opposite side. The participants then stepped back 2.5 shoe lengths from the wall and repeated the movement (Level 2). Inability to touch the wall five consecutive times without loss of balance at two shoe lengths from the wall on both sides was considered failure.

INTER-RATER RELIABILITY

Each participant self-screened themselves using the Symmio application. The participants followed the standard video guidance and instructions from the application using a tablet (iPadOS, 15.6.1, 9th generation) while a healthcare professional simultaneously scored each movement in real time. The healthcare professional (TAN) was a physical therapist (PT) trained in evaluating the Symmio movements. The participants nonverbally recorded their scores in the Symmio application and on a data collection form. The PT rater stood far enough away from the participants to remain blinded to the participants’ scores. The participant’s self-screen scores and the PT rater’s observed scores for each Symmio test were compared to establish inter-rater reliability.

DISCRIMINANT VALIDITY

To determine the validity of Symmio, scores on individual components of the self-screen were compared to established movement screening and motor control testing procedures. Two PTs who were certified in the FMS™ and YBT-LQ™ performed all functional testing and were blinded to the Symmio results. To improve reliability, the same PT performed the FMS™ (RJR) to appraise movement dysfunction while the other PT tested dynamic balance deficits with the YBT-LQ™ (EV).

1. **Pain with Movement**: Any subjective report of pain, which was defined as discomfort beyond normal stretch or soreness, with any of the physical testing was considered painful.\(^5\)

2. **Functional Movement Screen**: This screening tool is used to identify limitations or asymmetries in seven movement patterns that are key to functional movement quality. The FMS™ consists of the overhead deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability tests which are each scored
on a four-point ordinal scale. Procedures and scoring for the FMS™ were consistent with recommendations from Cook et al.26 Failure was defined as a score of a 1 (movement limitation) or asymmetry on any individual FMS™ movement patterns.27

3. Y Balance Test-Lower Quarter: The YBT-LQ™ tests tri-planar dynamic balance near the limits of an individual’s stability. Testing procedures and scoring were consistent with the protocol and testing kit developed by Plisky et al.28 Failure was defined as an anterior reach asymmetry >5.5 cm, posteromedial and posterolateral asymmetries >5.5 cm, or ankle dorsiflexion ROM limitation (<40°) or asymmetry (>5°).29

STATISTICAL METHODS

Descriptive statistics including means and standard deviations (SD) were calculated. Inter-rater reliability for the categorical scores of each component of Symmio was compared between both raters using Cohen’s kappa coefficient with 95% confidence intervals (CI 95%) and percent absolute agreement. The Cohen’s kappa coefficient quantifies the strength of agreement and was interpreted as: 0.01-0.20 = none to slight, 0.21-0.39 = fair, 0.40-0.60 = moderate, 0.61-0.80 = substantial, >0.81 = near perfect.30

The accuracy of Symmio to discriminate between participants with pain, movement dysfunction, and dynamic balance deficits was determined using cross-tabulations. The presence of pain, movement dysfunction, and dynamic balance limitations were dichotomized as described previously and entered into separate 2x2 tables. Univariate analyses were performed using the chi-square test for categorical variables to evaluate significant differences between Symmio performance and the presence of pain, movement dysfunction, or dynamic balance deficits. A Fisher’s Exact test was used to measure the association if one or more cells had an expected count of less than five. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), likelihood ratios (LR), and odds ratios (OR) were calculated with 95% confidence intervals to describe the accuracy of the Symmio self-screen to detect MSK risk factors. All data analyses were performed with R for Mac OS 4.1.2 statistical software (RStudio for Mac, Version 1.4). An alpha level of $p < 0.05$ was considered statistically significant for all tests.

RESULTS

Demographic information for all participants is provided in Table 1. Eighty participants completed all testing procedures, and the data were used for analysis. The mean age ± SD of the participants in this sample was 26.5 ± 9.4 and ranged from 18 to 68 years old. All participants reported engaging in some physical activity with 80% (n=64/80) reporting that they were moderately or highly active. A total of 25% (n=20/80) of participants reported current pain with activities of daily living before testing.

INTER-RATER RELIABILITY

Results for the inter-rater reliability (kappa, 95% CI, and % agreement) for both raters are presented in Table 2. Cohen kappa values ranged from fair to near perfect agreement between both raters. The tandem toe touch tests had the highest inter-rater reliability with Cohen kappa values that ranged from 0.85 (95% CI, 0.68-1.0) to 0.90 (95% CI, 0.77-1.0) and represented near perfect agreement. The bal-
 ance and reach test at 2.5-foot lengths from the wall demonstrated the lowest inter-rater reliability with Cohen kappa scores ranging from fair to moderate agreement on the left (k=0.34, 95% CI, 0.20-0.48) and right (k=0.45, 95% CI, 0.26-0.60) leg, respectively.

PAIN WITH MOVEMENT

The accuracy of Symmio to discriminate between those who had pain with movement on the FMS™ is reported in Table 3a. The chi-square test showed a significant association for the 2x2 contingency table created (χ²=8.73, p=0.003) for participants’ reporting pain with movement on the FMS™ and Symmio. The Symmio Self-Screen was 74 percent (95% CI, 0.63-0.83) accurate in identifying pain with movement on the FMS™. The sensitivity (0.71, 95% CI, 0.49-0.87) and specificity (0.75, 95% CI, 0.62-0.86) for detecting the presence of pain with functional movement were only marginally different. Participants with pain on the FMS™ were 2.8 times (+LR=2.85, 95% CI, 1.68-4.77) more likely also to have pain on Symmio. Overall, participants who had pain on the FMS™ were 7.29 (95% CI, 2.51-21.2) greater odds of reporting pain on Symmio compared to those without pain on the FMS™.

MOVEMENT DYSFUNCTION

The 2x2 table created to examine the discriminant validity of Symmio to identify movement dysfunction compared to the FMS™ is presented in Table 3b. There was a significant association between the presence of poor movement quality on the Symmio Self-Screen and failure of the FMS™ tests which were more mobility focused (χ²=15.67, p=0.001). The diagnostic accuracy of Symmio to capture mobility dysfunction on the FMS™ was 73 percent (95% CI, 0.62-0.82). There was no significant association between the presence of movement dysfunction on the FMS™ and Symmio when failure on the FMS™ was defined as the presence of 1’s or asymmetries (p=0.31), or when failure was defined as a composite score of less than 14 (p=0.33).

DYNAMIC BALANCE DEFICITS

The 2x2 table created to examine the discriminant validity of Symmio to identify poor dynamic balance compared to the YBT-LQ™ is presented in Table 3c. There was a significant association between individuals who failed the Symmio Self-Screen and poor performance on the YBT-LQ™ (X²=9.13, p=0.005). Poor performance on Symmio had a 69 percent (95% CI, 0.57-0.79) accuracy in detecting individuals who also failed the YBT-LQ™. The Symmio Self-Screen demonstrated similar sensitivity (0.69, 95% CI, 0.55-0.82) and specificity (0.68, 95% CI, 0.49-0.83) for detecting the presence of dynamic balance deficits. Participants who scored poorly on Symmio were more than two-fold more likely (+LR=2.15, 95% CI, 1.25-3.70) to have dynamic balance deficits on the YBT-LQ™ with an odds ratio of 4.76 (95% CI, 1.81-12.5).

DISCUSSION

The goal of the Symmio Self-Screen is to create MSK health awareness through a user-friendly electronic application that the general public can administer without dependence on a trained healthcare professional. The findings from this study support the primary hypothesis that untrained individuals can reliably administer the Symmio application to self-screen for MSK risk factors that may contribute to physical limitations and determine the need for further evaluation by a healthcare professional. All subtests of Symmio, scored as pass or fail, exhibited fair to near perfect inter-rater reliability between both raters regardless of their movement screening experience.

Movement screening performed by trained healthcare providers or fitness coaches has demonstrated moderate to excellent levels of agreement. Additionally, untrained individuals with limited experience screening movement have demonstrated the ability to reliably screen movement. Leeder et al. reported that untrained practitioners with limited clinical experience were able to correctly identify dysfunction in the FMS™. Likewise, high school baseball coaches with no screening experience and minimal training were able to screen movement quality similarly to a clinician with 10 years of expertise in movement screening. However, the investigation of self-appraisal of functional movement in untrained, non-healthcare individuals is a novel concept.

To the authors’ knowledge, this is the first study to examine the ability of untrained individuals to screen their own movement patterns without the aid of an external observer. Participants without previous knowledge of the Symmio scoring criteria could follow the application's in-

<table>
<thead>
<tr>
<th>Table 1. Descriptive Characteristics of Participants (n=80)</th>
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<td>Highly active</td>
</tr>
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</table>

*SD=standard deviation, y=years, n=count

International Journal of Sports Physical Therapy
structional video and score similarly to a trained healthcare provider. Each Symmio subtest was dichotomized as pass or fail with clear biomarkers for success which likely reduced the scoring complexity and minimized errors among the participants. Other movement screening tools and assessments such as the FMS™, Selective Functional Movement Assessment (SFMA™), and Landing Error Scoring System (LESS) have more complex scoring criteria or more category scoring options which is more suitable for trained professionals.\textsuperscript{35,36}

It is particularly important for untrained individuals who are administering a self-screen to have a simplified scoring system to maximize reproducibility. Interestingly, the balance and reach subtest, which is like the anterior reach of the star excursion balance test (SEBT), demonstrated only fair to moderate agreement and had the lowest agreement of all the Symmio subtests. In a systematic review, Powder et al.\textsuperscript{11} reported excellent inter-rater reliability (0.88, 0.85-0.96) and intra-rater reliability (0.88, 0.84-0.95) on the anterior reach of SEBT. In the current study, the participants performing the balance and reach test may have had difficulty perceiving when their stance leg heel lifted off the ground which may have been more apparent to a trained observer.

The findings from this study partially support the secondary hypothesis that the Symmio tests can accurately discriminate between individuals with or without MSK risk factors. The Symmio subtests were comprehensive enough to reproduce painful movement similar to the FMS™. Painful movement on the FMS™ has been shown to be a meaningful risk factor associated with seven-fold increased injury risk.\textsuperscript{8} However, an association between movement dysfunction and asymmetries or overall composite score on the FMS™ and Symmio was lacking. Though a stronger association between Symmio performance and FMS™ results was expected, it is interesting to note that Symmio demonstrated a higher specificity (0.75, 95% CI, 0.62-0.86) for detecting the presence of movement dysfunction on the FMS™ mobility tests compared to sensitivity (0.71, 95% CI, 0.49-0.87). Participants with movement dysfunction on the FMS™ mobility tests were nearly three times (+LR=2.86, 95% CI, 1.35-4.88) more likely to also have dysfunctional movement on Symmio. Overall, participants who demonstrated dysfunctional mobility tests on the FMS™ were more than seven (7.40, 95% CI, 2.60-21.0) times greater odds of performing poorly on Symmio compared to those who passed. Symmio was intentionally designed to have a mobility bias to reflect current research findings linking mobility deficits to future injury risk.\textsuperscript{57,58} Saddler et al.\textsuperscript{59} reported that individuals with limited hamstring flexibility were more likely to develop low back pain, whereas, ankle dorsiflexion restrictions can increase the odds of an injury and medical discharge in Army recruits.\textsuperscript{40,41} The creation of a patient-driven, self-screening tool for the reliable detection of MSK risk factors can alert individuals of impending MSK needs. The Symmio self-screen can allow individuals to seek evaluation and treatment prior to MSK injury, which may lead to decreased healthcare dollars spent on preventable issues. Future research should explore the prospective longitudinal correlation between poor Symmio performance and the development of MSK conditions throughout the lifespan.

LIMITATIONS

This study is not without limitations. First, the prevalence of MSK risk factors was high in this sample limiting confidence in the interpretation of PPV and accuracy due to the oversaturation of risk factors. This is especially true when screening movement dysfunction and dynamic balance as the accuracy does not exceed the upper bound 95% CI for the prevalence. Second, the mean age of participants was relatively young at 26.5 ± 9.4. This decreases generalizability, as the sample may not reflect the general population. Although the sample included individuals in their 50s and 60s, most participants were college-aged limiting generalization throughout the lifespan. Third, only 15% of participants reported current pain prior to testing, but many more experienced pain during the movement and balance testing. Though the goal of Symmio is to detect these issues, the mismatch in awareness may have impacted results. Finally, the reference standards used to establish the criterion validity of Symmio did not include additional movement-based screens beyond the FMS™ and YBT-LQ™. Although comparison utilizing other movement-based screens could be meaningful, the authors determined that no other movement-based screen or dynamic balance test has been as robustly examined in relation to reliability, predictive validity, and modifiability as the FMS™ and YBT-LQ™.

CONCLUSION

The Symmio Self-Screen application is a reliable, user-friendly, and feasible screening tool that can be used to identify MSK risk factors including pain with movement, movement dysfunction, and dynamic balance deficits in untrained, non-healthcare individuals. This application can be used by the general public to create awareness of the user’s current movement health and encourage preventative action before the development of disability.

ACKNOWLEDGMENTS

The authors of this study would like to thank the University of Evansville Doctor of Physical Students Mattie Franklin, Skylar Walden, Rachel Howey, and Kris Bale for their assistance with study organization and data collection.

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Table 2. Inter-rater Reliability of Symmio Tests (n=80)

<table>
<thead>
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<th>Symmio Test</th>
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<td>L Tandem Toe Touch – Front toe touch</td>
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<td>0.85 (0.68, 1.0)</td>
</tr>
<tr>
<td>R Shoulder Mobility – Paper grab</td>
<td>0.65 (0.28, 1.0)</td>
</tr>
<tr>
<td>L Shoulder Mobility – Paper grab</td>
<td>0.86 (0.67, 1.0)</td>
</tr>
<tr>
<td>R Shoulder Mobility – Fingertips touch</td>
<td>0.84 (0.71, 0.96)</td>
</tr>
<tr>
<td>L Shoulder Mobility – Fingertips touch</td>
<td>0.87 (0.76, 0.98)</td>
</tr>
<tr>
<td>R Rotation – Feet together</td>
<td>0.49 (0.17, 0.81)</td>
</tr>
<tr>
<td>L Rotation – Feet together</td>
<td>0.47 (0.03, 0.91)</td>
</tr>
<tr>
<td>R Rotation – Tandem stance</td>
<td>0.70 (0.53, 0.86)</td>
</tr>
<tr>
<td>L Rotation – Tandem stance</td>
<td>0.59 (0.40, 0.78)</td>
</tr>
<tr>
<td>Deep Squat – Fingertips to ground</td>
<td>0.74 (0.57, 0.91)</td>
</tr>
<tr>
<td>Deep Squat – Fists to ground</td>
<td>0.67 (0.50, 0.83)</td>
</tr>
<tr>
<td>R Balance and Reach – 2-foot lengths</td>
<td>0.49 (0.25, 0.73)</td>
</tr>
<tr>
<td>L Balance and Reach – 2-foot lengths</td>
<td>0.62 (0.37, 0.87)</td>
</tr>
<tr>
<td>R Balance and Reach – 2.5-foot lengths</td>
<td>0.43 (0.26, 0.60)</td>
</tr>
<tr>
<td>L Balance and Reach – 2.5-foot lengths</td>
<td>0.34 (0.20, 0.48)</td>
</tr>
<tr>
<td>Mean</td>
<td>0.68 (0.47, 0.87)</td>
</tr>
<tr>
<td>SD</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*R=right, L=left, 95% CI=95% confidence interval
### Table 3. Accuracy of Symmio to Detect Musculoskeletal Pain and Dysfunction (n=80)

<table>
<thead>
<tr>
<th>Pain on FMS™</th>
<th>Fail FMS™ Mobility</th>
<th>Fail YBT-LQ™</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Symmio</strong></td>
<td><strong>Yes</strong></td>
<td><strong>No</strong></td>
</tr>
<tr>
<td>Yes</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>No</td>
<td>7</td>
<td>42</td>
</tr>
</tbody>
</table>

\[ X^2 = 8.73, p \text{ value } = 0.003 \]

\[ X^2 = 15.67, p \text{ value } = 0.001 \]

\[ X^2 = 9.13, p \text{ value } = 0.003 \]

<table>
<thead>
<tr>
<th>Est.</th>
<th>95% CI</th>
<th>Est.</th>
<th>95% CI</th>
<th>Est.</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>0.74</td>
<td>0.63, 0.83</td>
<td>0.73</td>
<td>0.62, 0.82</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Prevalence</strong></td>
<td>0.30</td>
<td>0.20, 0.41</td>
<td>0.65</td>
<td>0.54, 0.75</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Odds Ratio</strong></td>
<td>7.29</td>
<td>2.51, 21.2</td>
<td>7.40</td>
<td>2.60, 21.0</td>
<td>4.76</td>
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<tr>
<td><strong>Sensitivity</strong></td>
<td>0.71</td>
<td>0.49, 0.87</td>
<td>0.71</td>
<td>0.57, 0.83</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Specificity</strong></td>
<td>0.75</td>
<td>0.62, 0.86</td>
<td>0.75</td>
<td>0.55, 0.89</td>
<td>0.68</td>
</tr>
<tr>
<td>+ LR</td>
<td>2.83</td>
<td>1.68, 4.77</td>
<td>2.85</td>
<td>1.46, 5.53</td>
<td>2.15</td>
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<tr>
<td>– LR</td>
<td>0.39</td>
<td>0.20, 0.74</td>
<td>0.38</td>
<td>0.24, 0.62</td>
<td>0.45</td>
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<tr>
<td>PPV</td>
<td>0.55</td>
<td>0.36, 0.73</td>
<td>0.84</td>
<td>0.70, 0.93</td>
<td>0.77</td>
</tr>
<tr>
<td>NPV</td>
<td>0.86</td>
<td>0.73, 0.94</td>
<td>0.58</td>
<td>0.41, 0.74</td>
<td>0.58</td>
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</tbody>
</table>

*FMS=Functional Movement Screen, YBT-LQ=Y Balance Test-Lower Quarter, +LR=Positive Likelihood Ratio, -LR=Negative Likelihood Ratio, PPV=positive predictive value, NPV=negative predictive value*
REFERENCES


International Journal of Sports Physical Therapy


Case Reports

The Development of a Return to Performance Pathway Involving A Professional Soccer Player Returning From A Multi-Structural Knee Injury: A Case Report

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This case report describes a male professional soccer player returning to match play (English Championship League) following a medial meniscectomy that occurred during the course of rehabilitation after Anterior Cruciate Ligament (ACL) reconstruction. The player underwent a medial meniscectomy eight months into an ACL rehabilitation program and following 10 weeks of rehabilitation successfully returned to competitive first team match play. This report outlines description of the pathology, the rehabilitation progressions, and the sports specific performance requirements of the player as they progressed through the return to performance pathway (RTP).

The RTP pathway included nine distinct phases with evidenced based criteria required to exit each phase. The first five phases were indoor as the player progressed from the medial meniscectomy, through the rehabilitation pathways to the "gym exit Phase". The gym exit Phase was assessed with multiple criteria: a) capacity; b) strength; c) isokinetic dynamometry (IKD); d) hop test battery; e) force plate jumps; and f) supine isometric hamstring rate of force (RFD) development qualities to evaluate the players readiness to start sport specific rehabilitation. The last four phases of the RTP pathway are designed to regain the maximal physical capabilities (plyometric and explosive qualities) in the gym and included the retraining of on-field sport specific qualities utilizing the 'control-chaos continuum.' The player successfully returned to team play in the ninth and final phase of the RTP pathway. The purpose of this case report was to outline a RTP for a professional soccer player who successfully restored specific injury criteria (strength, capacity and movement quality), physical capabilities (plyometric and explosive qualities), and on-field sport specific criteria utilizing the 'control-chaos continuum.'

Level of Evidence
Level 4

INTRODUCTION

ACL injuries are one of the most troublesome and debilitating injuries in professional soccer often resulting in career threatening consequences. In European professional soccer an ACL injury occurs at a rate of 0.066 per 1000 hours of training or match play.1,2 This equates to 0.4 ACL injuries per team per season which means there will be on average one per team every two seasons.3 The average length of time a player is side-lined is 241 (± 65) days highlighting the severity of this injury.3 Only 55% of athletes post ACL surgery to return competitive sport4 and in soccer following ACL surgery only 65% of players were still competing at the same level three years post-surgery.3 In professional soccer ACL reinjury rates are also high at 17.8%3 with
pressure to return players back into competition as quickly as possible. Webster et al. have reported this may be because of practitioners continuing to use time-based criteria instead of criteria-based outcomes as only 23% of athletes have completed objective functional criteria prior to return to sport (RTS). van Melick et al. has recommended the use of strength tests, hops tests, and on-field sports specific assessments during ACL rehabilitation before a RTS is permitted. Further work by Kyritsis et al. highlighted athletes were at four times greater risk of sustaining an ACL graft rupture when they fail to meet six well defined criteria (IKD testing at 60, 180 and 300°/s, single leg (SL) hop, SL triple hop, SL crossover hop, and on-field sports-specific assessments) than those who have passed RTS criteria.

The first phases of a RTS program include the diagnosis and planning Phase, the acute management and contralateral limb loading Phase and finally the Phase for restoration of normal movement and early loading. Following these three phases is the gym Phase 4. Gym Phase 4 starts the rehabilitation process of the forementioned injury specific criteria including strength, capacity, and movement quality. In gym Phase 5 the athlete is objectively evaluated for a) capacity, b) strength, c) isokinetic dynamometry (IKD), d) hopping using a hop test battery, force plate jumps, and f) supine isometric hamstring RFQ qualities to ensure a safe transition into grass Phase 1.

On entering grass Phase 1 an athlete begins to retrain their on-field sport specific criteria utilizing the 'control-chaos continuum.' This starts with high control and low variability exercises as an athlete completes simple ball exercises and low intensity running (<65% maximum speed) to regain confidence and aerobic fitness. Further power qualities are also evaluated in grass Phase 1 (SL triple hop, SL medial hop and SL countermovement jump) to ensure that a >90% limb symmetry index (LSI) and pre-injury scores had been achieved. In grass Phase 2, running speeds (<85% maximum speed) and the intensity of sports specific actions are increased as controlled chaos and multidirectional actions were used. Underpinning grass Phase 2 was also the restoration of all explosive qualities (SL drop jump, IKD peak torque at 0.18ms and supine isometric hamstring RFQ at 100ms) to ensure a >90% LSI and pre-injury scores had been achieved before entering grass Phase 3. Grass Phase 3 consists of high chaos and high variability through positional specific exercises where a maximum speed and intensity was employed. Exposing an athlete to exercises of a similar physical, technical and cognitive demand to team training was the aim which provided the necessary base for grass Phase 4. During grass Phase 4 the athlete is reintroduced to team training and return to match play. The purpose of this case report was to outline a RTP for a professional soccer player who successfully restored specific injury criteria (strength, capacity and movement quality), physical capabilities (plyometric and explosive qualities), and on-field sport specific criteria utilizing the 'control-chaos continuum.'

THE REHABILITATION TO PERFORMANCE PATHWAY

The RTP pathway (Figure 1) provides a clear plan and a progressive pathway for injured players, members of the multidisciplinary team (MDT) and coaches to follow. The philosophy has nine distinct Phases: 1-5 are predominately gym based, Phases 6-8 blend grass and gym rehabilitation, and Phase 9 is the training transition Phase. The injured player and members of the MDT go through the pathway in a step-by-step manner to provide a safe and successful RTP after injury.

In Phase 1 the initial injury has taken place. Examinations, scans and consultations are provided as required. An accurate and early diagnosis is fundamental, and the RTP plan is clearly communicated to the player. In gym Phase 2 the injured player starts acute management and can continue contralateral limb exercising when able. Treatment is given daily as the acuteness of the injury subsides. In gym Phase 3 (Figure 1) the injured player regains normal movement patterns through gait retraining and starts to initiate early injury loading with basic exercises such as double leg (DL) squats, lunges, bridge patterns and also heel raises exercises for the calf complex. Achieving fundamental exercise patterns without the injury reacting which is determined by an increase in pain levels (increase greater than >1 on a numerical rating scale) and effusion levels (an increase measured using the stroke test grading system) is paramount to start the rehabilitation pathways in gym Phase 4. Appropriate pacing and honest communication during the first three phases help to manage and synchronize expectations of the player, coaches, and members of the MDT.

Gym Phase 4 is a key phase of the process when the player and injured structures start to recondition through the eight rehabilitation pathways and the step-by-step progressions (Figure 2). These rehabilitations pathways are programmed utilizing a daily undulating periodization (DUP) method as this allows for daily variations in intensity and volume (Figure 3).

The pathways all work on the theme of graded exposure and by varying the rehabilitation stimuli daily it is more conducive to neuromuscular adaptations than concurrent training. Each of the rehabilitation pathways targets a different physical quality and by alternating these through DUP superior adaptations can be achieved (Figure 3). Developing each of these eight rehabilitation pathways in gym Phase 4 provides three distinct advantages to the injured player: progressive exposure and adaptation of the tissue, variability through the eight distinct pathways, and confidence and trust in the injury.

The rehabilitation theme of DUP is continued in gym Phase 5 which consists of the gym exit profiling where five of the rehabilitation pathways are objectively profiled (Figure 2). The plyometric pathway (hop battery and force plate [dual force plate system at 1000Hz, PASPORT force plate, model number: PS 2141; Pasco Roseville, CA, USA and integrated force plate form customized software package, NMP ForceDecks] jump profiling) and injury specifics
Figure 1. The rehabilitation philosophy visualized in the 9 Phased 'Return to Performance Pathway.'

(RDLs = Roman deadlifts. IKD = Isokinetic dynamometry. COD = Change of direction. CMJ = Countermovement jump. RFD = Rate of force development. Hams = Hamstrings. Max = Maximum, Accels = Accelerations, Decels = Decelerations, GPS = Global positioning system.)
pathway (SL supine isometric hamstring RFD qualities) are practiced, and data is observed but are more formally assessed utilizing the force plates during the grass rehabilitation phases. The injury specifics pathway is used to address any outlying metrics that are not covered in the other pathways and deemed to be relevant for that specific injury or player. In this case, the measurement of the players SL supine isometric hamstring RFD qualities due to this being an ACL with a hamstring graft were considered important to assess.10,36 The five pathways are rarely completed all in one day as they stress different physical qualities such as strength (maximum strength profiling)9,10 and IKD, [BIODEX, Biodex system 3, Biodex Medical System Corp., NY, USA] profiling) endurance (capacity profiling) and movement quality (running preparation profiling and indoor ball skills profiling). Despite the development from the outset of plyometric and explosive qualities in gym Phase 4 the completion of the power hop battery,19–21 counter movement jump profiling22–24 and RFD (SL drop jump).25 IKD quadriceps peak torque at 0.18ms28 and isometric hamstring RFD at 100ms26 profiling occur in a sequential fashion later in the pathway. Plyometric profiling being completed during the grass Phase 1 (Figure 5B) and explosive qualities like RFD profiling during grass Phase 2 (Figure 5C).

For a player to start the grass Phase 1 it is paramount to have adequately fulfilled the running preparation pathway and achieved >90% LSI and pre-injury scores on the non-negotiable prerequisites in gym Phase 5 (Figure 4A). These specifically involve the capacity profiling (SL squat,11 calf raise gastrocnemius bias and soleus bias,12 hamstring bridge in 90° and 30°),13 the maximum strength profiling (SL leg press, rear foot elevated split squat, [RFESS] trap bar deadlift and barbell floor thrust),9,10 and IKD profiling (quadriiceps and hamstrings concentric tests) involving five reps at 60%/ and 15 reps at 300%/27–39

After successfully exiting gym Phase 5 the player starts grass Phase 1, "jogging and reintroductions". During this phase the player is gradually exposed to their individualized match day total distances, typically running at speeds <65% of their maximum speed. It is a first step with high control and low variability as it aims to reintroduce the player to low intensity ball drills and regain aerobic fitness through 100m pitch runs27 and Hoff drible circuits.40 Despite grass Phase 1 having an outdoor theme there are still necessary indoor gym parameters that need to be achieved to progress: >90% LSI and pre-injury scores in their power profiling (SL triple hop,19–21 SL medial hop,19,21 SL countermovement jump height and flight time:contraction time) (Figure 5B).22–24

During grass Phase 2, high speed running (HSR) and change of direction drills (COD) are developed with a gym focus on RFD. All grass intensities are below 85% of their maximum (speed and volume parameters) while the final RFD characteristics are achieved in the gym. During grass Phase 2 achieving >90% LSI and pre-injury scores in their RFD profiling (SL drop jump height and reactive strength index [RSI],25 IKD quadriceps peak torque at 0.18ms28 and isometric hamstrings RFD at 100ms)26 along with their grass metrics is the prerequisite to progress. In grass Phase 3 the player is exposed to their maximum speeds, intensities, and specific positional demands as the exercises are chaotic and highly variable.27 Intensities above 85% place an exponential load on the tissues59 and it is vital all strength, power and RFD profiling has been completed to >90% LSI and pre-injury scores to ensure safety before they enter the grass Phase 3 (Figure 5C).

Throughout grass Phase 3 the player completes positional drills and achieves maximum speeds in preparation for grass Phase 4 where they will transition into team training and match play. It should not be forgotten that despite gym metrics been achieved regularly exposing the player to the appropriate strength, power and RFD stimuli may reduce their risk of reinjury and improve their athletic performance. Once in grass Phase 4 the player trains in a normal pattern with the rest of the team as they increase their match exposure in a pragmatic fashion depending on their length of injury.

CASE PRESENTATION

A 26-year-old male professional soccer player with no previous history of injuries sustained a traumatic right knee injury. The player had a history of having played 300 professional matches as a midfielder / forward. He was a predominantly right footed player and had an average playing mass of 78kg and height of 176cms.

Mid-way through the first half of a competitive match he received shoulder contact from an opposing player during a deceleration action. This contributed to a change in the following two to three steps of his normal deceleration pattern forcing his right knee into the classic dynamic valgus position of abduction, flexion, and internal rotation.41 The knee was in the 'position of no return' leading to an instant rupture of the ACL.42,43

After being removed from the field of play the initial examination showed reduced range of knee flexion 80° and an unwillingness to actively or passive extend the knee into hyperextension. The ACL was absent on Lachman testing and the player was experiencing high levels of pain 7-8/10 on a numerical rating scale.29 Within 48 hours a magnetic resonance imaging scan (MRI) was performed which confirmed a full thickness rupture of the ACL and partial thickness tears of the posterior horn to the medial and lateral menisci. The PCL and collateral ligaments were intact and there was no chondral damage.

Within seven days the player was assessed by an orthopaedic surgeon and the decision was made to have a surgical intervention. The plan was clearly outlined to the player: it would take a minimum of nine months to return to competitive sport and there was a 30-40% chance the medial meniscus repair might fail and require further surgical intervention at some stage.44,45 The surgical opinion was that initially repairing the medial meniscus would reduce the tension on the harvested ACL graft in the early phases of the rehabilitation process.46–48 The player underwent a successful 90-minute operation during which the surgeon harvested a four-strand autologous hamstring
Figure 2. Showing the ‘Rehabilitation Pathways and Progressions’ of gym Phase 4 and the gym exit profiling in gym Phase 5.

semimembranosus and gracilis graft from the contralateral limb (left leg). This was inserted into the right knee as the new ACL. The player underwent meniscal repair of the posterior horn sections of both the medial and lateral menisci.

The player initially completed eight months of ACL rehabilitation. In accordance with Buckthorpe and Della Villa’s work, this consisted of three distinct stages of ACL rehabilitation. Stage 1 was the early stage (Figure 1, gym Phases 2 and 3) where focus was placed on the player reducing pain and swelling and recovering normal gait and activities of daily living. Following this, the player went into the mid-stage (Figure 1, gym Phases 4 and 5) to regain muscular strength, power, and movement quality before entering the final sports specific stage to redevelop the underlying explosive qualities and necessary soccer qualities to perform with the team. At the eight-month stage (Figure 1, grass Phase 2) despite the player completing HSR and COD drills on the grass the player felt a sharp pain in the medial aspect of the right knee during some routine hopping exercises. An MRI revealed he had re-torn the surgically repaired posterior horn of the medial meniscus. This distinct possibility had been outlined from day 1 so despite initial disappointment and frustration it was not a shock to the player or his support team. The player underwent the necessary medial meniscectomy of the posterior horn, and the following outlines the 10-week rehabilitation the athlete engaged in after the meniscectomy, in order to return to competitive soccer.

INTERVENTION

GYM PHASES 1, 2 AND 3 – ‘EXPECTATIONS’

The aim of the first 3 phases (Figure 1) were to set the expectations and prepare the player for the loading and progressive gym Phase 4. Holistic care begins in all injuries during Phase 1 (diagnosis and planning). In this case the player underwent the necessary scans, consultations, and a surgical intervention to the posterior horn of the medial meniscus of his right knee. A routine surgical operation excised the small section of the posterior horn that was loose and simultaneously allowed for an arthroscopic examination of the previously reconstructed ACL and the lateral meniscus that were both reported to be healing well. Absolute clarity in communication between all members of
the MDT during Phase 1 was paramount. The player and his support team inside and outside of the club along with the coaches were given clear understandable information about what had happened and the process ahead. Addressing and agreeing on the expectations of all the key people helps to start the process in a realistic and unison manner.

The acute and contralateral limb loading Phase (Figure 1 - Phase 2) lasted for the first seven days post-surgery. Wound management was prioritized along with daily use of the game ready (Model GRPro 2.1, Betchworth House 57-65 Station Road Redhill. RH1 1DL. UK.) to reduce post-surgical swelling and pain. Effleurage massage and range of motion exercises were used to restore mobility especially into knee flexion and extension and to reduce the formation of a capsular contraction. Controlled non-weight bearing exercises and the Compex muscle stimulator (electrical muscular stimulation was performed with model No SP 8.0, MI-scan, wireless, 120 mA, 400 us, 150 Hz. Guildford, Surrey, GU28XG, UK.) were used to address muscular atrophy and regain normal muscular recruitment patterns. Also in this Phase, contralateral limb exercise training and cardiovascular conditioning (seated battle ropes, boxing, upper body circuits, core and arm bike) sessions were completed to complement the nutritional advice given (provided by team nutritionist) and to maintain team involvement for the player wherever possible.

This player exited gym Phase 2 at seven days post-surgery. For this, he exhibited full knee extension, flexion of >125°, the grading of a trace of joint effusion measured by the stroke test (Scale - Zero = No wave produced on downstroke. Trace = Small wave on medial side with downstroke. 1+ = Larger bulge on medial side with downstroke. 2+ = Effusion spontaneously returns to medial side after upstroke [no downstroke necessary]. 3+ = So much fluid that it is not possible to move the effusion out of the medial aspect of the knee]) and a pain level never above 2/10 on a numerical rating scale. He had strictly adhered to the prescribed protocol, was competent in his non-weight bearing exercises and had subsiding pain and swelling levels. Patience within and respect during these first two phases allowed the player to appropriately start the gym Phase 3.

With a low pain score (<2/10 numerical rating scale) and trace joint effusion the player progressed into the gym Phase 3 to start early loading and regain normal movement patterns (Figure 1). Competency in the fundamental weight bearing exercises and gait variations was the primary goal of this phase. Firstly, he completed the key exercises like squats, lunge patterns, Roman deadlifts (RDL), heel raises, and gait exercises with reduced body weight in the pool and was then transitioned to the gym. Movement quality was deemed to be a key factor and assessed visually to ensure there was no loss of balance, contralateral hip drop, ipsilateral knee valgus or any excessive trunk movement. During gym Phase 3 the player was required to complete 3 sets x 8 repetitions with normal movement strategies and no post-session reaction to be able to start gym Phase 4. By day 10 the player had achieved these criteria and could start the rehabilitation pathways outlined in gym Phase 4 (Figure 2). Experience suggests premature entry into gym Phase 4 will lead to recurrent episodes of swelling, pain and compensatory movement strategies that reduce the players well-being and overall confidence.
GYM PHASE 4 - REHABILITATION PATHWAYS AND PROGRESSIONS

This phase started at the 10-day mark post-surgery and continued into week four when the player started to complete the necessary gym exit profiling tests in gym Phase 5. The aim of gym Phase 4 was to expose the injured lower extremity to different physical demands through the variety of rehabilitation pathways outlined in Figure 2. The pathways are clearly outlined in a progressive manner as the demands increase in a step-by-step fashion ensuring the player and the injury can safely perform the profiling tests in gym Phase 5.

During gym Phase 4 not all the rehabilitation pathways were worked on each day as a DUP theme was applied throughout the week (Figure 3). For this player a normal working week consisted of rehabilitation days on Monday and Tuesday with Wednesday set as regeneration day. Similarly, Thursday and Friday were rehabilitation days and often Saturday was free to work on any specific aspects as required. Sunday was traditionally set as a day off which was aligned with normal team training schedules. The aim of the undulated process was to expose the player to the most complex and neuromuscular challenging demands at the start of the session and the safer exercises towards the end of the session when arguably he was more fatigued.

Similarly, the player completed more neuromuscular challenging pathways (indoor ball skills pathways, plyometric pathway, maximum strength pathway, IKD pathways and anaerobic and upper body type conditioning) on Monday and Thursdays when the player was most fresh compared to lower intensity and higher volume type sessions on Tuesday and Fridays (running preparation pathway, injury specifics pathways, capacity pathway, aerobic conditioning and core exercises) when the player had worked the previous day (Figure 3).

During gym Phase 4 there were eight key rehabilitation pathways to follow. The manner in which six of these progressed is highlighted in Figure 4. In the capacity pathway the player completed multiple exercises in his regular sessions but was critically assessed in five key SL exercises (squat, calf raise gastrocnemius bias and soleus bias and hamstring bridge in 90° and 30°). These are progressed from 3 sets of 8 repetitions to 2 sets to fatigue which was completed in the gym exit profiling in gym Phase 5. Gradually increasing the repetitions and sets developed a local muscular endurance and robustness in the joint to withstand the loads in preparation for the grass phases ahead.

Strength was addressed in the maximum strength and IKD pathways. With all strength progressions the repetitions were reduced as the load was increased. Again, the player had a variety of exercises for the posterior and anterior chain but was critically assessed in the SL leg press, RFESS, traphar deadlift, and the barbell floor thrust. Accompanying this the IKD pathway was initiated on the treatment table with manual resistance as the therapist resisted knee flexion and extension through range. This was then progressed to the IKD machine where initially quicker speeds (low joint forces) were employed. These contrac-

tion speeds were gradually decreased from 180°/s to 60°/s as the player ended by completing the traditional 3-speed profiling (60,180,300°/s) at the end of gym Phase 4 ready for the gym exit profiling in gym Phase 5.

The players power and RFD qualities were also introduced early in gym Phase 4. They were initially started through the introduction of the plyometric pathway which involved the player completing a drop series of squats and lunges in the pool on Mondays and Thursdays (Figure 3). This was progressed to the land with simple landings from a step and box (altitude landings). As the plyometric pathway progressed the introduction of the hop battery which consisted of the SL horizontal hop, triple hop, medial and lateral hop for distance tests as described by Ebert et al. and force plate jump profiling which consisted of DL and SL countermovement jump, along with DL and SL drop jumps leading into week four which included some of the types of simple hopping techniques the player was doing. The use of the force plates enabled the analysis of the relative force, RFD and interlimb asymmetries for example, to be compared to preinjury standards. Despite ongoing improvement and monitoring these qualities cannot be completely restored without the necessary grass speed exposures later in the process.

Movement patterns through the running preparation pathway were also completed specifically on Tuesday and Fridays (Figure 3) as the number of ground contacts increased from 100 in the first session to 600 by the end of gym Phase 4. Every time the foot hit the ground it was counted and calculated as a sum for the total session. This progressed from simple wall drills and sled walks to a skip (a skipping pattern in a linear direction emphasizing the hip drive phase of running) variations. By week 4 the player had increased the number of ground contacts so he was able to start gym Phase 5 where he would be expected to complete 800-1000 ground contacts in a session. This along with two running introduction sessions (60-75% progressing to 95% body weight) on the anti-gravity treadmill (Alber-G, Fremont, CA, USA.) further highlighted his readiness for the grass phases.

Gym Phase 4 encompassed the rehabilitation pathways and progressions and in this case lasted from 10 days into week 4. These step-by-step increases in each of the pathways emphasized the design of graded exposure and also the variability created through the different pathways. The player improved in his local muscular endurance (capacity pathway) and strength (maximum strength and IKD pathways). He also started to develop his power and RFD qualities (plyometric pathway). By adding the movement qualities that were practiced in his running preparation pathway and indoor ball skills pathway he was starting to develop a level of confidence in the gym. This self-confidence came from being pain free not only in these but in the wide variety of exercises and movements that gym Phase 4 included.

Having successfully completed the gym Phase 4 rehabilitation pathways described (Figure 2) he was ready to enter the gym Phase 5 (gym exit profiling).
GYM PHASE 5 - GYM EXIT PROFILING

The most common question a player asks at the start of the rehabilitation process is “when can I start running on the grass?” Gym Phase 5 has been specifically designed using objective tests to answer this question. The player had complete familiarity with the profiling modalities as they were gradually introduced throughout gym Phase 4. These standardized and repeatable profiling tests such as the hop test battery, force plate jumps were conducted regularly by all squad members as monitoring tests which added weight to their significance and relevance to performance. The common language they created was understood and well interpreted between the MDT, the player’s peers, and the coaches through ongoing education.

The structure of gym Phase 5 was conducted in complete alignment with the DUP of gym Phase 4. Gym Phase 5 was fundamentally an extension of gym Phase 4 with the exercises in the pathways being objectively profiled on the fourth and fifth day of week 4. On the fourth day the player completed the indoor ball skills profiling, plyometric profiling, the maximum strength and the IKD strength profiling. Despite a seemingly large volume of work, the indoor ball skills profiling (15 mins), the plyometric profiling (15 mins), the maximum strength profiling (30 mins) and the IKD profiling (15 mins) all took in total 75 minutes. Again, familiarity during gym Phase 4 to all these exercises reduced the players time to completion in one session.

The indoor skills pathway had seen the player progress through familiarization exercises with the ball which included exercises like the keep-up variations to lateral shuffles and volleys. The plyometric profiling (force plate jumps included the DL and SL countermovement and drop jumps with the hop battery including SL horizontal, triple, medial and lateral hop techniques) would not be equal to pre-injury levels at this stage but it was important the player could perform all tests without pain or compensatory movement patterns. Compensations were judged in real time in the frontal plane by observing a vertical line through the trunk, one line through the exercising limb and one line horizontally through the pelvis. Despite being subjective, suboptimal mechanics seen through this method are easy to assess and can be used as simple steps to coach the player to better movement quality. In summary the movement quality, overall confidence, and ability to complete the plyometric variations at this stage was a prerequisite to exit gym Phase 5.

The maximum strength profiling (Figure 4B) saw the player achieve 230kg on a 3-repetition maximum SL leg press and 35kg each arm during a RFESS. Later that fourth morning the player completed the IKD profiling. At this stage the key criteria to achieve were >90% LSI and pre-injury scores in the peak torque at 60°/s (strength), and the total workload for 15 repetitions at 300°/s (endurance) for the quadriceps and hamstring muscles (Figure 4C). For the strength and endurance IKD tests, the quadriceps were 96% and 94% respectively when utilizing the pre-injury ipsilateral maximum scores for comparison.

On the final workout day of the week the player started by completing the running preparation profiling. Through a variety of drills such as A skips (a skipping pattern in a linear direction emphasizing the hip drive phase of running), B skips (a skipping pattern in a linear direction emphasizing the hip extension phase of running) and heel flics for example, the player demonstrated the ability to complete 1000 ground contacts per limb in a movement session, a prerequisite for starting grass Phase 1. He also completed his final anti-gravity treadmill running session.

The treadmill session followed on from the previous session that ended while running at 75% body weight. Two-minute running intervals at 12.6 km/hour (3.5ms⁻¹ / 40% of maximum speed) with a stepwise increase from 80 to 95% body weight was successfully achieved. This was in exact alignment with the planned running intervals of the upcoming first session of grass Phase 1 in the following week. Later in the final day of the week the player completed low-level control and balance exercises as injury specific exercises. Movement quality while maintaining limb, pelvic and trunk alignment was the focus as SL rotational and balance type exercises were conducted.

To conclude gym Phase 5 the player completed the capacity profiling. This involved the player completing as many repetitions as possible on five key exercises. Throughout gym Phase 4 he had worked on numerous variations of these exercises like in all pathways but these five were specifically chosen to be profiled. From Figure 4A, the player exceeded >90% LSI and pre-injury ipsilateral maximum scores. Scores of 67 repetitions for the SL gastrocnemius heel raise, and 80 repetitions for the hamstring bridge in 90° and the SL squat exercise were achieved (Figure 4A). These tests along with hamstring bridges in 30° and SL soleus heel raise were used to measure the capacity of the lower limb musculature. Comparisons between limbs and exceeding >90% of his pre-injury ipsilateral maximum scores provided the player with the feeling of confidence to safely enter the grass Phase 1.

To exit gym Phase 5, it was important to utilize a holistic approach. Four key factors were interpreted together to make a safe and calculated decision that the player was ready to start grass Phase 1. Firstly, he had achieved >90% of his pre-injury ipsilateral maximum scores in his capacity, maximum strength and IKD profiling (Figure 5A). These key pathways were the cornerstone of his rehabilitation at this stage. Secondly it is widely acknowledged that the power (hop test battery - Figure 4D, and countermovement jump profiling - Figure 4E) and RDF (SL drop Jump IKD quadriceps peak torque at 0.18ms² and isometric hamstring RDF at 100ms) qualities will lag at this stage, but the player had started to go through the progressions and was comfortable with all exercises of the plyometric pathway (Figure 2). Thirdly, although not purely objective, the player had completed other pathways like the running preparation and indoor ball skills (Figure 2) which further highlighted his competency in a variety of movement patterns and also to tolerate load. Finally, and arguably the most critical factor was the psychological confidence the collective of all the pathways had provided the player. At this stage expecting the player to feel ready to resume playing is unfeasible. However, verbalizing his confidence and readiness (>90%
confidence) to start on the grass was imperative for him to commence grass Phase 1 at the start of week 5. This simple confidence scale (≥90% confidence) was used at the end of each phase to ensure communication between the player and therapist ensuring the player felt psychologically ready to start the next phase.

GRASS PHASE 1 – JOGGING AND REINTRODUCTIONS

The aim of grass Phase 1 in week five was twofold. Firstly, to reintroduce the player to ball activities and jogging on the grass whilst increasing his level of aerobic fitness and secondly to develop the necessary power qualities in the gym to start HSR and COD drills in grass Phase 2. In grass Phase 1 despite the player working on the grass, off-feet conditioning, and gym work continued in unison with very specific targets after the profiling completed in gym Phase 5. This player needed to accomplish the necessary power qualities assessed through the hop battery19–21 and SL countermovement jump profiling.22–24 Specifically achieving >90% LSI and pre-injury scores ipsilateral maximum scores in these key power tests was required to exit grass Phase 1 (Figure 5B).

On the grass the player completed sessions that involved pitch length runs (1 pitch length 100m x 5 = 500m),10 dribble circuits (Hoff dribble circuit 290m x 1 = 290m)60 at a low speed (<65% maximum speed <5.1 ms⁻¹) to increase his aerobic fitness level. As the player progressed through grass Phase 1 the total distance he covered in each session improved by 1km each day to 6km from a starting point of 2km. Incrementally increasing the number of pitch runs and dribble circuits was conducted in a step by step process as this type of aerobic conditioning has proven to achieve a heart rate <85% maximum.10,62,63 Accompanying this he was reintroduced to simple passing (0–10m), ball manipulations and low-level patterning drills that were incremen-
Figure 5. The prerequisite criteria to be achieved before the player progressed through each of the grass phases.

A) GYM EXIT CRITERIA Achieved Pre-Grass Phase 1 - Jogging and Re-Introductions. B) POWER CRITERIA Achieved Pre-Grass Phase 2 - HSR and COD Drills. C) RFD CRITERIA Achieved Pre-Grass Phase 3 - Maximum Speed and Positional Drills. D) ALL CRITERIA Achieved Pre-Grass Phase 4 - Training Transition. (Yellow: Maximum distance achieved in one session in metres. Light Blue: Maximum number of accelerations and decelerations achieved in one session. Gray: Maximum number of changes of directions achieved in one session. Dark Blue: Maximum distance of high-speed running achieved in one session (>5.7 m s\(^{-1}\)). Red: Maximum distance of sprint metres achieved in one session (>7.3 m s\(^{-1}\)). Maximum speed achieved in one session (ms\(^{-1}\)). R = Right. Reps = Repetitions. Nm = Newton metres. CMJ = Countermovement jump. RSI = Reactive strength index. Ms = milliseconds. HSR = High speed running. COD = Change of direction. RFD = Rate of force development.)

tal advancements to the exercises he had completed during the indoor ball skills pathway. He had no exposure to HSR or high-level accelerations and decelerations (>2.5 m s\(^{-1}\)) as the high control and low variability ball drills were confined to distances no greater than 4 meters. However, with the sensitivity of the global positioning system (GPS sys-
tem - augmented 10 Hz Apex, Catapult Leeds, UK) he did record some low-level (<2.5 m.s\(^{-1}\)) COD (total in one session 47, 27% of match total volume, Figure 6C) and accelerations and decelerations (total in one session 49, 31% of match total volume, Figure 6B). All these short distance intensity type actions were controlled and included within the small area (4m maximum) patterning drills the player completed. Grass Phase 1 was conducted in week five post-surgery and contained in total of five grass sessions. Critically during Phase 1 aerobic conditioning was implemented in the form of 500m runs (1 pitch length 100m x 5) and Hoff dribble circuits.60 During this and simple passing drills the player regained some confidence in his body, had a reintroduction to ball drills and accumulated 18,800 meters at a low speed, with 5523m being the highest achieved in one session (Figure 6A).

To complement the running and ball work the player also prioritized power work in the gym during grass Phase 1. Crucial to this whole RTP philosophy was the blending of the grass and gym exercises both being addressed simultaneously to prepare the player for the next phase he would progress onto. At this point in grass Phase 1 he needed to complete the necessary power profiling (hop battery\(^{19–21}\) and SL countermovement jump testing)\(^{22–24}\) to ensure the player was adequately prepared and safe to start grass Phase 2. During the morning sessions specific cueing was utilized to direct the players intent in producing explosive movements. The player completed three power sessions (day 1, day 4 and day 6 in the week) which consisted of the profiling criteria and supplementary power-based exercises (squat jumps, lunge jumps, step jumps, and hurdle hop variations etc). The power profiling (part of the plyo-
metric pathway) specifically focused on the hop test battery\textsuperscript{19–21} and the SL countermovement jump.\textsuperscript{22–24} The results of the hop test battery significantly improved with the key hops for this injury being the SL triple hop (625cms) and the SL medial hop (152cms) both exceeding >90% LSI and pre-injury ipsilateral maximum scores (102 and 101% respectively, \textbf{Figure 5B}). Similarly, the SL countermovement jump height (24.2 cms) and the flight time:contraction time ratio (0.58 ms\textsuperscript{-1}) for this player had achieved pre-injury levels of 94 and 95% respectively (\textbf{Figure 5B}). To exit grass Phase 1 the player had completed the GPS criteria (5-10m passing, low intensity COD, accels and decels, aerobic runs with a maximum of 6km in one session, all metrics <65% in speed, intensity, and volume) and also the necessary power criteria (\textbf{Figure 5B}) which were the prerequisites to start grass Phase 2.

GRASS PHASE 2 – HIGH-SPEED RUNNING AND CHANGE OF DIRECTION DRILLS

The aim of grass phase two was twofold. Firstly, it was on the grass to complete HSR (<85% of maximum speed), increase session volumes (<85% of match total volume in metres), complete reactive drills including CODs, accelerations and decelerations (<66% of match total volumes) and also to complete some longer kicking exercises (<40m) (\textbf{Figure 1}). All of these requirements were within the controlled chaos and multidirectional themes of the ‘control-chaos continuum’.\textsuperscript{27} The second aim was in the gym where the final RFD qualities (SL drop jump,\textsuperscript{25} IKD quadriceps peak torque at 0.18ms\textsuperscript{26} and isometric hamstring RFD at 100ms)\textsuperscript{26} were achieved again with a prerequisite to exit grass Phase 2 being set at >90% LSI and pre-injury ipsilateral maximum scores (\textbf{Figure 5C}).

During grass Phase 2 (week 6) the player continued the theme of DUP. On day 1 and day 4, the player completed more intensity-based drills including short distance (0–20m), accelerations, decelerations and CODs. Conversely on day 2 and day 5, he completed a more extensive HSR theme at the start of the session and an accumulation of low intensity meters towards the end of the session. Daily warmups of either rotational and more flexed positions or more upright HSR mechanics reflected these grass themes to prepare the player appropriately. Towards the end of the grass Phase 2 in the day 4 session the player had completed in total 91 accelerations and decelerations (57% of match total volume - \textbf{Figure 5B}) and 109 COD (62% of match total volume - \textbf{Figure 5C}). On day 5 the player accumulated 350m of HSR (peak speed 7.2ms\textsuperscript{-1} = 85% of maximum speed – \textbf{Figure 5F}) in this extensive day and a total of 6523m in his largest volume session (\textbf{Figure 5A}). Concurrent to the physical work was the ball work where the player completed longer passing type exercises specifically on the intensive days (day 1 and day 4).

During grass Phase 2 in addition to the HSR and reactive drills the player also prioritized RFD work in the gym. RFD was deemed to be the last quality to be completed in the gym\textsuperscript{61} and a non-negotiable prerequisite to start the maximum speed work in grass Phase 3. The development of the player’s RFD had started beginning at 10 days post-surgery as the player engaged in the plyometric pathway (\textbf{Figure 2}). Also, by undertaking all of the rehabilitation pathways and achieving qualities like capacity, strength (\textbf{Figure 4A}) and power (\textbf{Figure 4B}) this could finally be accomplished. By replicating the periodization of the power work in grass Phase 1 the player completed pre-grass sessions on day 1, day 4 and day 6 in the week programmed around the theme of RFD. A variety of exercises such as hamstring isometrics, drop jumps and hurdle bounds were employed to increase limb stiffness and utilize the fast stretch shortening cycle (<250ms ground contact times),\textsuperscript{59,61} Minimal repetitions (2-4) and maximum intent was employed as the player’s RFD qualities were profiled in numerous ways. As \textbf{Figure 5C} highlights >90% LSI and pre-injury scores was specifically required in the SL drop jump (jump height and RSI),\textsuperscript{25} the RFD of the quadriceps peak torque on the IKD at 0.18ms (at 180°/s)\textsuperscript{26} and the isometric RFD in the hamstrings (3 x 3s isometric holds) on the force plates at 100ms (\textbf{Figure 4F}).\textsuperscript{26} By the end of week six the player had successfully completed grass Phase 2 as he had achieved the GPS criteria (\textbf{Figure 1}) and the necessary RFD criteria (\textbf{Figure 5C}) which were the prerequisites to start grass Phase 3.

GRASS PHASE 3 – MAXIMUM SPEED AND POSITIONAL DRILLS

At seven weeks post-surgery, the player started grass Phase 3. The aim of this phase was to achieve maximum GPS metrics (\textbf{Figure 1}) and work on any rehabilitation residuals that he had not accomplished. On the grass the phase involved maximum speed work (>95% of maximum speed), increased session volumes (>95% of match total volume in metres), positional drills including CODs, accelerations and decelerations (>95% of match total volumes) and also to complete positional kicking in this case namely shooting drills (\textbf{Figure 1}). The second aim of grass Phase 3 was in the gym. If there are no major asymmetry to work on like in this case, then continuing to monitor essential variables is the focus such as RFD and maximum strength qualities for example. Grass Phase 3 was periodized in a similar theme (intensive days on day 1 and day 4 and extensive plus volume (low intensity) days on day 2 and day 5) to grass Phases 1 and 2. This was in alignment with the team’s training schedule except the hardest day of the week in RTP was on day 5 as opposed to day 6 (match days) for the team. On the extensive days (day 2 and day 5) the player achieved a speed of 8.4 ms\textsuperscript{-1} (\textbf{Figure 6F}), 153m sprint meters (\textbf{Figure 6E}) and 580m of HSR (\textbf{Figure 6D}) which equated to 99%, 101% and 106% of his match metrics respectively. The second part of his day 5 session included conditioning (high volume at low intensity) as he accumulated a total session distance of 9515m (95% of match total metres). Conversely intensive metrics were similarly developed as he achieved in one session 139 accelerations and decelerations (\textbf{Figure 6B}) and 151 subsequent COD (\textbf{Figure 6C}) (87% and 85% respectively of match total volumes). Chaotic and highly variable movement patterns were individualized for the player through positional drills and shooting drills.\textsuperscript{27} Similarly controlled collision exercises with the physio and peers were designed...
to build confidence by replicating his injury mechanism and prepare him for team training in grass Phase 4.

Despite the player achieving >90% LSI and pre-injury ipsilateral maximum scores in the maximum strength (Figure 5A) and RFD profiling (Figure 5C) the player subjectively wanted to maintain these training habits and qualities. He valued their link to performance and his preparation sessions on day 1 and day 4 continued to favor a RFD theme. Conversely after his grass sessions on the day 2 and day 6 he completed a concise maximum strength exposure (3-4 sets x 3-4 repetitions). Accompanying these positives themes the player subjectively felt 90-95% ready to train (Figure 5D) which is also another key psychological prerequisite to be achieved prior to starting with the team in grass Phase 4.

**GRASS PHASE 4 – TRAINING TRANSITION**

To enter grass Phase 4 at eight weeks post-surgery the player had completed the three grass phases exposing him to the necessary GPS demands (Figure 1) and also accompanying gym profiling (Figure 5D). Clinically he presented with no pain or swelling in his knee. He had experienced no major setbacks during the 8 weeks post-surgery and self-rated his readiness to train at >90%. During grass Phase 4 he rejoined full team training, exposing him to full contact and the inevitable neurocognitive overload that team training brings. The training speeds, spaces and interaction with players and coaches’ instructions undoubtedly overloaded the player, so unnecessary increases in the physical demands were not prioritized.27 In the gym the player continued a bi-weekly prophylactic strength exposure in the key exercises he perceived to be benefiting his knee (RFESS, SL leg press, glut-hamstring bench raises, Nordic hamstring exercises, and the IKD, at 3 sets x 5 repetitions at 60°/s).38 His preparation sessions consisted of RFD exercises to ensure the RFD in the concentric and eccentric phases were continuing to improve. Both the strength and RFD sessions contained some of the key profiling tests (for example, strength exercises RFESS, SL leg press and IKD at 60°/s and RFD exercises such as SL drop jump and supine isometric hamstrings) now being employed as simple monitoring exercises to check for any subsequent trending patterns. The detection of any possible drop offs could be addressed early with the appropriately prescribed prophylactic strength or RFD sessions pre or post training. After two weeks of full team training the player took part in a behind closed door friendly match where he successfully played 45 mins. This was followed, five days later, with another 45 minutes in a friendly match situation. These match minutes were further increased to 75 and 90 minutes before the player played in his first full league match. Similarly, he built up his competitive match minutes from 25 to 45 to 75 as he regained match fitness.

**SUMMARY**

The purpose of this case report was to outline a RTP for a professional soccer player who successfully restored specific injury criteria (strength, capacity and movement quality), their physical capabilities (plyometric and explosive qualities), and the retraining of their on-field sport specific criteria utilizing the ‘control–chaos continuum’. The player went through the nine-phase RTP pathway linking the pathology, the development of physical qualities in the gym, and also sport specific qualities on the grass. The pathway utilizes clearly outlined exit criteria for each phase and demonstrates how each of the phases were progressed by graded exposure in the gym and on the grass utilizing the ‘control–chaos continuum’. Furthermore, the provided pathway presents how the players physical qualities were developed in a sequential fashion with capacity and strength developed first followed by plyometric and explosive qualities. The RTP pathway has clear phases, and exit criteria, a philosophy that is not limited by static time-based markers but instead uses objective and performance-related criteria. By achieving a LSI of >90% and pre-injury scores it allowed the player to complete the process as quickly as possible while ensuring he was safe to return to competition.

**CONFLICTS OF INTEREST**

The authors report no conflicts of interest.

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The Longitudinal Neurophysiological Adaptation of a Division I Female Lacrosse Player Following Anterior Cruciate Rupture and Repair: A Case Report

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Background

Neurophysiological adaptation following anterior cruciate ligament (ACL) rupture and repair (ACLR) is critical in establishing neural pathways during the rehabilitation process. However, there is limited objective measures available to assess neurological and physiological markers of rehabilitation.

Purpose

To investigate the innovative use of quantitative electroencephalography (qEEG) to monitor the longitudinal change in brain and central nervous systems activity while measuring musculoskeletal function during an anterior cruciate ligament repair rehabilitation.

Case Description

A 19 year-old, right-handed, Division I NCAA female lacrosse midfielder suffered an anterior cruciate ligament rupture, with a tear to the posterior horn of the lateral meniscus of the right knee. Arthroscopic reconstruction utilizing a hamstring autograft and a 5% lateral meniscectomy was performed. An evidence-based ACLR rehabilitation protocol was implemented while using qEEG.

Outcomes

Central nervous system, brain performance and musculoskeletal functional biomarkers were monitored longitudinally at three separate time points following anterior cruciate injury: twenty-four hours post ACL rupture, one month and 10 months following ACLR surgery. Biological markers of stress, recovery, brain workload, attention and physiological arousal levels yielded elevated stress determinants in the acute stages of injury and were accompanied with noted brain alterations. Brain and musculoskeletal dysfunction longitudinally reveal a neurophysiological acute compensation and recovering accommodations from time point one to three. Biological responses to stress, brain workload, arousal, attention and brain connectivity all improved over time.

Discussion

The neurophysiological responses following acute ACL rupture demonstrates significant dysfunction and asymmetries neurocognitively and physiologically. Initial qEEG assessments revealed hypoconnectivity and brain state dysregulation. Progressive enhanced brain efficiency and functional task progressions associated with ACLR rehabilitation had notable simultaneous improvements. There may be a role for
monitoring CNS/brain state throughout rehabilitation and return to play. Future studies should investigate the use of qEEG and neurophysiological properties in tandem during the rehabilitation progression and return to play.

BACKGROUND AND PURPOSE

Injury to the anterior cruciate ligament (ACL) causes an immediate functional disparity to knee joint proprioception and the central and peripheral nervous systems. The neurological and physical alteration in joint mechanics warrants targeted interventions to regain functional performance. Clinicians rely on progressive physical and neurological best practice intervention techniques to advance and guide rehabilitation and functional performance that leads to return to play sport parameters. After injury or surgery clinicians are presented with the challenge to improve or correct mechanical dysfunctions including bilateral and/or ipsilateral asymmetries in balance, strength, coordination, and reacquisition of skills. Recent data indicates the changes that occur in musculoskeletal or physical performance during the rehabilitation process may be ill-proportioned to the improvements noted by the central and peripheral neurological systems following ACL rupture and repair.

Immediately post-injury there are drastic changes to the both afferent (sensory) and efferent (motor) components of the peripheral nervous system which results in disrupted proprioceptive and motor function. Activity at the brain and central nervous system (CNS) are therefore impacted by deficits in the neurophysiological somatosensory, motor excitability, and neural connective pathways throughout the body. The ligament rupture results in an altered feedback loop and changes of CNS processing of somatosensory information and concomitant alterations in motor responses. Patients struggle to accurately maintain kinesthetic awareness, joint position awareness, the accuracy of the velocity of movements, and muscle forces necessary to function appropriately. As a result, recent literature supports the use of treatment protocols that target somatosensory processing in the CNS in tandem with the management of impairments of pain, swelling, joint instability, and motor dysfunction. The impaired feedback from ligament rupture results in advanced stages of disaffirmations and degenerative neuroplastic modifications that result in insufficient efferent motor responses, and lead to functional limitations related to lack of body/limb coordination, postural control issues, and gait deviations. For these reasons, researchers and clinicians attempt to target neural adaptation of both the peripheral and central nervous systems. Neural adaptation following a significant alteration in afferent activity is well documented in the literature for joint replacement where numerous afferents are lost and other systems adapt to provide proprioception-like afferents. While acute neural changes have been monitored in the brain during functional activities, there is very little empirical real-time evidence of central brain neural modifications sequentially throughout the progressions of a post-ACL repair/rehabilitation program. Thus, monitoring brain and central nervous system performance throughout a rehabilitation program may provide objective metrics to improve the neuromuscular training and neurophysiological development needed during rehabilitation following an injury, such as a ruptured ACL.

Quantitative electroencephalography (qEEG), commonly referred to as “Brain Mapping” is the utilization of a digitized signal to analyze changes in brain function and performance. Measuring feedback loops between sensorimotor stimuli and functional tasks allows clinicians to measure cortical electrical brain wave activity. These measures can be used to evaluate a variety of conditions thought to be rooted to the brain, such as, post-traumatic stress disorder (PTSD), attention disorders, autism, epilepsy, seizure disorders, dementia, headaches, traumatic brain injuries, sleep disorders and learning disorders. qEEG applies sophisticated mathematical and statistical analysis to the brain wave patterns and compares these observations to an universal database compiled of numerous healthy controls representing a variety of ages and genders. The qEEG system used in this study has added technological advances that allow for dynamic activities to be performed during the qEEG data collection, resulting in a more profound assessment of qEEG and neurophysiological metrics as part of a rehabilitation program for an ACL rupture. Such measures display real-time brain electrical activity that occurs during physical activities. The Cogninics (CGX) Quick- 20r v2, 21 channel state of the art dry EEG headset (CGX EEG) from CLR Neurotechnics, Inc (Manhattan Beach, CA), with LED impedance indicators is used to collect continuous electrical signals from the brain that measure the magnitude and timing of cortical activity across 19 active channels (with 2 reference channels) relative to a stimulus or a motor task. Cortical activity can be evaluated in response to a stimulus or functional task associated with the specific action.

A well-functioning and active brain is classified as being in a regulated ready state with efficient brain connectivity as indicated by the red/orange highlights on a qEEG brain image. Two brain maps are presented in Figures 1a and 1b. Figure 1a represents a well-regulated state with little inhibitory drive which indicates efficient brain connections. Figure 1b represents an inhibited neurophysiological state indicating poor efficiency of brain connectivity. The image in Figure 1b was obtained within 24 hours of knee post-injury. The blue tints seen in Figure 1b are indicative of a dysregulated and poor electrical active brain state. The type and strength of the electrical impulses or brain waves can be analyzed to determine how different parts of the brain function and communicate during a given task. For example, different EEG signals: delta (0.5–4 Hz), theta (4–7 Hz), and alpha (8–12 Hz) waves have multifaceted cortical sensory integrations used to promote motor activity that can reflect a motor and/or sensory activity period. Memory tasks are associated strictly with theta and alpha waves typically involved with inhibition or deactivation of sensorimotor activities. Evaluating the
strength in electrical activity and band frequency of the brain waves throughout the cortex can quantitatively reflect the activity associated with a physical task.\textsuperscript{10}

There are limited data identifying the cortical changes that occur throughout the linear progression of an ACLR rehabilitation program. Documenting the electrophysiological changes and accommodations at the brain and/or central nervous system level while progressing cognitive and physiological motor tasks used post-ACL injury or surgery may be valuable in developing more precise exercise progressions and return-to-play decisions. The purpose of this case report was to investigate the innovative use of qEEG and neurophysiological metrics to monitor the longitudinal and simultaneous change in brain and central nervous system activity while measuring musculoskeletal function during an anterior cruciate ligament repair rehabilitation.

CASE DESCRIPTION

SUBJECT DEMOGRAPHICS

A 19-year-old, right-handed, Division I NCAA female lacrosse midfielder with 10 years of playing experience suffered a full thickness mid-substance anterior cruciate ligament rupture and a vertical posterior horn tear of the lateral meniscus near the intercondylar notch of the right knee. Clinical evaluation revealed moderate capsular swelling and a dysfunctional limb with pain during gait. Joint laxity following a Lachman’s anterior drawer, pivot shift, valgus, and varus stability tests revealed excessive anterior tibial translation and a grade 1 MCL and LCL sprain. The injury occurred on 01/24/2022, and findings were confirmed the same day via MRI. An arthroscopy with anterior cruciate ligament reconstruction using hamstring tendon autograft and a 5% lateral meniscectomy was performed on 01/28/2022. The subject volunteered to take part in the case study and signed an informed consent regarding patient confidentiality and the protection offered by the U.S. Health Insurance Portability and Accountability Act (HIPAA). This project received no outside funding and the research was completed by the University of Cincinnati Sport Science Research Team.

During the course of the rehabilitation program, the patient’s central nervous system, brain performance and musculoskeletal function were monitored longitudinally at three separate time points: twenty-four hours post ACL rupture, one month following ACLR surgery and ten months following ACLR surgery. Brain wave activity was observed using a CGX EEG head set at each time point. Congruently, the athlete participated in a contemporary evidence-based ACL rehabilitation protocol throughout all time points as outlined in Appendix A: Rehabilitation Summary Outline.\textsuperscript{11,12} The expected limitations in functional mobility early in the rehabilitation progression restricted some physical testing during the early testing dates; however, normal rehabilitative functional parameters were implemented to assure return to play status over time.

EXPLANATION OF OUTCOME MEASURES

Brain activity-dependent variables were measured using the CGX EEG head set. Cognitive workload metric, cognitive attention metric, sensorimotor rhythm (SMR) asymmetry, galvanic skin response (GSR), and three-dimensional cortex connectivity were derived to account for the central nervous system and brain precision and efficiency.\textsuperscript{13} Cognitive workload metric represents the depletion of mental resources of the brain due to higher levels of cognitive or sensory demands placed on the brain.\textsuperscript{14} GSR measures sympathetic conductance and electrical activity via a skin electrode which offers insight into the emotional state, or arousal, of a subject under specific experimental conditions. CNS arousal is typically directed by the thalamus with an emphasis on processing sensory inputs from the vision and hearing centers of the brain.\textsuperscript{15} Brain attention refers to a person’s ability to attain, remember, understand, and apply information.\textsuperscript{15} Heart rate (HR), heart rate variability (HRV), respiration rate (RR), peripheral body temperature, and superficial trapezius EMG activity were measured. Increases in HR, RR, and trapezius EMG activity are associated with elevated levels of central nervous system stress or increased GSR, whereas, HRV decreases with higher levels of stress.\textsuperscript{15}

Neurocognitive and physical psychometric measures consisted of the Stroop test,\textsuperscript{16,17} visual reaction,\textsuperscript{17,18} a reaction time test,\textsuperscript{17} musculoskeletal range of motion, strength, a functional movement assessment consisting of balance-mobility-gait tasks,\textsuperscript{11,12} and force plate outputs for jump and landing mechanics on a ForceDecks (VALD Performance, Charlotte NC) force plates.\textsuperscript{19,20} The Stroop test is a neuropsychological test used to assess the speed or ability to process cognitive interference, inhibition, and selective attention capacity relative to simultaneous stimuli.\textsuperscript{16,17} The visual reaction was measured using the Dynavision D2, (Cincinnati, OH) A* Proactive assessment which requires the individual to react and strike lights as they il-
luminate as quick as possible when presented in a random, computer-selected algorithm. In a similar fashion, the decision reaction time tests measured the response speed of the left and right hand and left-to-right brain activity precision prompted by visual stimuli. The functional movement and force plate assessments were used to measure bilateral functional asymmetries and relative ground reaction force upon walking gait, balance, landing, and jumping activities. Specifically, the force plate offers insight to force acceleration/decelerations, reactions, and bilateral imbalances. Overall, each measure provides an initial marker for longitudinal progressions that offer insight to assist in monitoring changes in functional performance and left-to-right symmetries of the limbs and brain function. The data was analyzed using CLR Neurosthetics, Inc neuroanalytics provided by Intheon Labs (San Diego, CA).

The initial qEEG assessment was performed twenty-four hours following injury while the athlete was being monitored and treated to manage the acute stage swelling and pain. Non-weight bearing/crutch ambulation, ice, compression, elevation, and linear mobility exercises were initiated to promote improvement in passive and active ROM with reductions in pain and swelling. The state of the acute injury limited the ability to perform extensive functional and physical assessments. Immediately following injury, the reduction in the motor neuron network demonstrates a potentially altered signal from the peripheral receptors. Therefore, the initial tests used to monitor neurophysiological status using qEEG were the physiological regulatory measures, the Stroop test, decision reaction time, attention, workload, and SMR metrics. There was no pre-injury baseline.

One month post-surgical reconstruction, the athlete was progressing through a best-practice rehabilitation program previously reported to have sustainable, valid, and reliable techniques ideal for athletic populations and return-to-play progressions. Throughout the rehabilitation protocol the athlete progressed with improvements noted in pain, swelling, ROM, function, and functional joint stability.

OUTCOMES

Heart rate, heart rate variability, respiration, and brain attention levels yielded high-stress Determinants in the acute stages of injury were associated with brain dysregulation, hemispheric asymmetries (Tables 2 and 3) and musculoskeletal functional asymmetries. Traditional objective measures of knee joint laxity, range of motion, swelling, strength, and patient-reported outcomes were collected throughout the rehabilitation progression and are outlined in Tables 4, 5, and 6. Central nervous system, brain performance, and musculoskeletal functional biomarkers were monitored longitudinally at three separate time points following anterior cruciate injury: twenty-four hours post ACL rupture, one month, and nine months which was the time period for her return to competition following ACLR surgery. Brain and musculoskeletal dysfunction longitudinally reveal a neurophysiological acute compensation and recovering accommodation from time points one to three. In addition, biological responses to stress, neuroanalytics of brain workload, arousal, and attention all advanced to more commonly regulated function during the progression of the rehabilitation. The neurophysiological development following acute ACL rupture demonstrates significant dysfunction in asymmetrical functions both neurocognitively and physiologically.

DISCUSSION

The original intent of this case was to investigate the innovative use of qEEG and neurophysiological metrics to monitor the longitudinal and simultaneous change in brain and central nervous systems activity while measuring musculoskeletal function during an anterior cruciate ligament repair rehabilitation. The data captured initial brain dysregulation and signs of accommodation that were simultaneously associated with muscular dysfunction over the nine-month period. Other authors have monitored only qEEG activity during isolated positional (kinesthetic) activity or only active ROM to demonstrate changes in brain wave activity. This is the first report to examine the use of the CGX EEG headset to perform a qEEG to evaluate and demonstrate simultaneous changes in both the central nervous system and the peripheral musculoskeletal system throughout an ACLR rehabilitation sequence.

The initial data regarding hemispheric asymmetries (Table 3) indicates the athlete's brain was in a dysregulated state at initial injury and one month following injury, but not at nine months following injury. A difference in brain activity, as little as 10-15% between each hemisphere, appears to create a dysregulated state. The initially slower right-handed reaction times indicate potential left hemisphere disruption as a result of having to accommodate for the injury to the right knee. In comparison, the left-hand reaction time was not clinically significant between time points one and two; however, it did demonstrate noted clinical improvements at nine months. The right hand was vastly different for all time points revealing a potential lag or inhibition in motor planning. The Dynavision D2 assessments from one month and nine months post-surgery revealed no significant change in performance which may indicate visual reaction time and accommodation following injury occur within the first month of rehabilitation and recovery. Recent literature has revealed both accuracy and reaction times to be impaired following ACLR. Conversely, this case data revealed slower reaction times following injury but no lag in accuracy. The results of the Stroop test remained constant throughout the rehabilitation program while the speed of responses significantly improved between each time point (Table 2).

The dysregulation noted in this case is likely multifactorial and associated with a compromised motor planning sequence. Recent literature has identified a potential inhibition response due to an increased strain on brain connectivity commonly associated with ACLR patients. The qEEG along with the neurophysiological measurements provides a clearer understanding of how the neural mapping of the dysregulated brain state and neurocognitive
Table 1. Attention, Workload, Sensory Motor Asymmetry, Heart Rate, Heart Rate Variability, Respiration Means and Standard Error of Measure.

<table>
<thead>
<tr>
<th>Dates/ Tasks</th>
<th>Attention #</th>
<th>Workload*</th>
<th>SMR Asymmetry*</th>
<th>Heart Rate</th>
<th>HRV</th>
<th>Respiration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
</tr>
<tr>
<td>1/25/21/</td>
<td>1.39</td>
<td>.007</td>
<td>.776</td>
<td>.003</td>
<td>77</td>
<td>.159</td>
</tr>
<tr>
<td>FMS, RT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/23/21/</td>
<td>1.17</td>
<td>.008</td>
<td>.752</td>
<td>.005</td>
<td>54</td>
<td>.379</td>
</tr>
<tr>
<td>FMS, RT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/14/21</td>
<td>1.02</td>
<td>.063</td>
<td>.731</td>
<td>.002</td>
<td>63</td>
<td>.464</td>
</tr>
<tr>
<td>FMS, FDT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FMS: Functional Movement Screen: functional gait and lower extremity landing tasks
RT: Reaction Time Task: used to assess speed and accuracy of decision making
T1= Time point of initial qEEG assessment (1/25/21)
T2= Time point of second qEEG assessment (2/23/21)
T3= Time point of third qEEG assessment (11/14/21)

Table 2. Longitudinal Change for Dynavision, Stroop Test, Stroop Reaction Time and Decision Reaction Time.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynavision (touch/min) AVE</td>
<td>NA</td>
<td>77</td>
<td>76</td>
</tr>
<tr>
<td>Stroop (ms)% Correct</td>
<td>97</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Stroop Response time (ms)</td>
<td>772</td>
<td>654</td>
<td>552</td>
</tr>
<tr>
<td>Reaction Time- Left Hand (ms)</td>
<td>445</td>
<td>428</td>
<td>395</td>
</tr>
<tr>
<td>Reaction Time- Right Hand (ms)</td>
<td>498</td>
<td>411</td>
<td>337</td>
</tr>
<tr>
<td>Reaction Time- L/R Average (ms)</td>
<td>462</td>
<td>410</td>
<td>366</td>
</tr>
</tbody>
</table>

T1 to T2, T2 to T3, T1 to T3 indicates assessment times 1= (1/25/2021), 2= (2/23/2021) and 3= (11/14/2021)
L/R= Left-to-Right hand reaction time average
*Indicates no immediate deficit in reaction time following injury

Table 3. Left to Right Hemisphere Symmetry, Percent Difference

<table>
<thead>
<tr>
<th>Date</th>
<th>Hemispheric Left</th>
<th>Hemispheric Right</th>
<th>Left-to-Right Hemispheric Differences</th>
<th>% Difference Left to Right hemisphere</th>
<th>Impression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/25/2021</td>
<td>847</td>
<td>718</td>
<td>129</td>
<td>15%</td>
<td>Dysregulated</td>
</tr>
<tr>
<td>2/23/2021</td>
<td>622</td>
<td>683</td>
<td>61</td>
<td>10%</td>
<td>Dysregulated</td>
</tr>
<tr>
<td>11/14/2021</td>
<td>566</td>
<td>539</td>
<td>27</td>
<td>2%</td>
<td>Regulated</td>
</tr>
</tbody>
</table>

Table 4. Knee arthrometry anterior tibial translation measures (mm) of involved and uninvolved knees by Newtons(N) of anterior force and time point from date of surgery.

<table>
<thead>
<tr>
<th>Knee Arthrometry (Knee Lax 3)</th>
<th>24 hours (initial)</th>
<th>1 month</th>
<th>6 months</th>
<th>9 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior Deficit 66(N)</td>
<td>-0.95mm</td>
<td>0.17mm</td>
<td>0.14mm</td>
<td>0.24mm</td>
</tr>
<tr>
<td>Anterior Deficit 88(N)</td>
<td>-0.94mm</td>
<td>0.01mm</td>
<td>0.29mm</td>
<td>0.23mm</td>
</tr>
<tr>
<td>Anterior Deficit 132(N)</td>
<td>-1.10mm</td>
<td>--</td>
<td>0.13mm</td>
<td>1.35mm</td>
</tr>
</tbody>
</table>

*Anterior tibial translation was measured with Knee Lax 3 device.
(N)- Newtons of Anterior Force.

Function are impacted during ACLR recovery. Bruns et al., reported hemispheric decoupling can be altered based on a task. Thought to be the result of lower corticospinal excitability in ACLR patients, lags in neurocognitive reaction time following injury appears to create a widespread cortical inhibition contributing to poor neural connectivity and peripheral motor response time. Reaction time and motor response play a vital role in athletic participation; thus, understanding the contributing factors of the CNS during ACLR recovery is critical to return to play progressions.
Table 5. Knee Range of Motion, and bilateral Symmetry Assessments for Swelling Circumference

<table>
<thead>
<tr>
<th>Time</th>
<th>24 hours (initial)</th>
<th>1 month</th>
<th>6 months</th>
<th>9 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Passive ROM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left: 5/0/145</td>
<td>Left: 5/0/145</td>
<td>Left: 4/0/145</td>
<td>Left: 5/0/145</td>
<td></td>
</tr>
<tr>
<td>Right: 0/3/75</td>
<td>Right: 0/1/110</td>
<td>Right: 4/0/140</td>
<td>Right: 5/0/140</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L/R ROM % Difference</th>
<th>Superior Patella: 0.5</th>
<th>Superior Patella: 0.3</th>
<th>Superior Patella: 0.0</th>
<th>Superior Patella: 0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference (cm)</td>
<td>Mid/Inferior Patella: 3.6/1.5</td>
<td>Mid/Inferior Patella: 2.2/0.7</td>
<td>Mid/Inferior Patella: 0.2/0.1</td>
<td>Mid/Inferior Patella: 0.1/0.0</td>
</tr>
</tbody>
</table>

| ACL-RSI | -- | 20% | 85% | 96.6% |

Knee Passive ROM: Goniometry range of motion in degrees
L/R ROM % Difference: Percentile difference in range of motion left to right limb compared
Knee Joint Swelling – Circumference: capsular swelling of the left to right limb compared
ACL-RSI: Anterior Cruciate Ligament Return to Sport After Injury scale – designed to measure an athlete's psychological readiness to return to sport after ACL injury

<table>
<thead>
<tr>
<th>Time</th>
<th>3 months</th>
<th>9 Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isometric 60°/s</td>
<td>Knee Extension</td>
<td>96%</td>
</tr>
<tr>
<td>Isometric 60°/s</td>
<td>Knee Flexion</td>
<td></td>
</tr>
<tr>
<td>Isokinetic 180 °/s</td>
<td>Knee Extension</td>
<td>--</td>
</tr>
<tr>
<td>Isokinetic 180 °/s</td>
<td>Knee Flexion</td>
<td></td>
</tr>
</tbody>
</table>

*Biodex Isokinetic Tests Measured in Degrees Per Second Peak Torque LSI%

In the current case, attention and workload metrics were elevated beyond normal levels immediately following injury and progressively decreased over time regardless of physical or visual tasks. The workload metric was notably different initially, likely due to the CNS accommodating following the injury.4,21,22 As a result, the initial workload values were elevated and trended higher with physical demands of jump landing, but not for the simple functional movements. The immediate elevation in the attention and workload metrics is consistent with previous reports of injury decreasing brain connectivity and efficiency following injury.22 The increased workload and attention are accommodation mechanics thought to stimulate alternative neuronal activity directed on returning peripheral limb function.21 In addition, when an individual is under high cognitive workload and the cognitive workload approaches the individual’s cognitive capacity, human errors often occur.14 Overall, hemisphere regulation was regained over an 8 month time frame, as indicated by a two-percent differential in brain hemisphere symmetries (see Table 3). It is important to note that the asymmetries that occurred in the central nervous system and brain regions of interest were associated with similaraccommodations and asymmetries in musculoskeletal function (See Tables 2 and 3).

Re-establishing normal function to the pre-injury level is the primary goal of rehabilitation after ACLR. The rehabilitation program used in the current case consisted of functional progressions normally seen in a traditional ACLR protocol. Return-to-play criteria rely on physical and clinical assessments related to range of motion, kinesthetic awareness, balance, and strength. The functional movement and force plate assessments used in the current study helped to guide the functional progressions necessary to advance movement patterns safely in preparation for return to sport. Throughout any rehabilitation process, left to right musculoskeletal asymmetries and functional capacities are used to evaluate exercise progressions. The current case reveals that monitoring the neurophysiological levels and brain electrophysiology activity in tandem with musculoskeletal function may be beneficial in maximizing return-to-play decisions post-injury or surgery.21,22

CONCLUSION

The objective of this paper was to demonstrate alterations in cortical brain activity after suffering an ACL injury and undergoing ACLR with the goal of returning to competition. The lack of cortical wave continuity, hemispheric asymmetries, and hemispheric decoupling throughout the phases of rehabilitation seem to support the need to monitor neurophysiological adaptations during rehabilitation to assure neural continuity between the peripheral and central nervous system.

The athlete advanced through the clinical pathway based on the traditional somatic metrics. While this case report demonstrates the novel use of qEEG to monitor brain neurophysiological somatic “readiness” for return to play/activity, more research is needed in order to support a causal relationship between these physical and neurological variables. Future studies with a larger cohort will be necessary to validate these conclusions. However, based on the data...
from this initial case study qEEG appears to have the potential to aid rehabilitation progressions by offering clinicians a collective insight into the neurological and physiological functional capacity of an ACLR patient.
REFERENCES


SUPPLEMENTARY MATERIALS

Appendix A

Clinical Commentary/Current Concept Review

Criteria-Based Rehabilitation Following Revision Hip Arthroscopy: A Clinical Commentary

Haley Leo, PT, DPT, Trevor Shelton, MD, MS, Helen Bradley, PT, MSc, SCS, CSCS

Keywords: criteria-based, rehabilitation, revision hip arthroscopy, physical therapy

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Hip revision arthroscopy is becoming an increasingly popular surgery for those with unsatisfactory outcomes following primary hip arthroscopy. With the relatively uncommon but potentially increased difficulty of rehabilitation from this surgery, a lack of established research regarding rehabilitative programs remains. Therefore, the purpose of this clinical commentary is to propose a criterion-based progression that considers the intricacies present following a hip revision arthroscopy from early rehabilitation through return to sport. Criteria are presented clearly to promote objective progression through rehabilitation as opposed to relying on time since surgery as revision surgeries do not always follow traditional tissue healing time-frames. This criterion based progression promotes range of motion (ROM), strength, gait, neuromuscular control, load introduction and gradual return to play.

Level of Evidence

5

INTRODUCTION

The number of revision hip arthroscopic surgeries is increasing substantially, due in part to the increasing number of initial arthroscopic labral repairs.1 In the last five years, there has been a significant increase in the overall number of arthroscopic hip surgeries, and the number continues to rise.2 As such, revision surgeries are becoming more frequent, with research indicating between 4–10% of initial cases will need a revision surgery.1–3 The mean time between primary labral and revision labral surgery is approximately two years.4,5 The most common indications for revision surgeries are residual bony impingement,4–9 labral tears,4–6,8,9 chondral lesions,5–7 micro-instability,5,9,10 and excessive scarring.4,5,8,9 Preoperative imaging studies show that nearly 80% of those seeking revision hip arthroscopy (RHA) surgery have signs of remaining bony impingement.4–9 Micro-instability can occur as a result of femoroacetabular impingement (FAI), soft-tissue deficiencies, such as labral insufficiency following debridement, capsular resection, or over-resection of bony impingement.9–12 Micro-instability may be a pain generator due to excessive physiologic motion and can put the capsule and labrum at risk for further injury.10–12

Studies investigating the outcomes of physical therapy following hip arthroscopy for labral pathology are limited.13 Thorborg and colleagues reviewed outcomes at one year post-operatively and found clinically relevant and statistically significant changes in function following post-operative rehabilitation for FAI and labral pathology. However, the patient related outcomes still fell behind those of healthy individuals.14 One review found that less than 50% of surgeons performing hip arthroscopy had an associated rehabilitation protocol given to patients.15 Of these protocols, use of bracing, weight bearing status, range of motion (ROM) precautions and limitations, and return to activity timelines varied significantly.15 When no residual bony impingement is present the variations found in both surgical and rehabilitative approach and treatment may be contributing to suboptimal outcomes following primary hip arthroscopy.

The utilization of criteria-based protocols to aid progression of rehabilitation is growing in popularity in other areas of orthopedics. In the anterior cruciate ligament (ACL) population, utilization of a criteria-based progression has been shown to reduce risk of reinjury four-fold.16,17 Following a shoulder stabilization procedure, significant numbers of participants did not pass criteria testing at the expected time of “recovery.”18,19 The use of
criteria-based progression versus time-based progression throughout rehabilitation should help to minimize the discrepancy in readiness for return to activity due to regular assessment of patient progress. These progressions can ensure patients move through each phase of rehabilitation and meet specific goals related to motion, neuromuscular control, and strength. The unique difficulties following RHA surgeries can differ from the traditional rehabilitation process and challenge the rehabilitation professional.

Previous clinical commentaries have outlined rehabilitative guidelines for those following primary labral reconstruction or repair, and although these studies present an excellent and thorough framework, they do not consider the additional factors that impact revision labral surgeries. This clinical commentary attempts to highlight the differences and present guidelines that are both criterion-driven and time-based to ensure consideration for the individual as well as the complexity of the surgical procedure. Therefore, the purpose of this clinical commentary is to propose a criterion-based progression that considers the intricacies present following a hip revision arthroscopy from early rehabilitation through return to sport.

FEMOROACETABULAR IMPINGEMENT

The primary anatomical considerations that contribute to labral pathology are attributable to femoroacetabular impingement (FAI). FAI is caused by the abnormal morphological anatomy that changes joint contact between the head/neck of the femur and the margin of the acetabulum. As such, the presence of FAI may be correlated with chondral and labral damage in patients with hip pain. There are three main types of FAI: cam impingement, pincer lesions, or combined impingement. Cam lesions consist of a non-spherical femoral head which can lead to impingement during flexion. This impingement in flexion may cause labral tearing or avulsion from the acetabular rim and potentially damage to the acetabular cartilage. Pincer impingement is typically due to acetabular overcoverage, sometimes in conjunction with coxa profunda or acetabular retroversion. This type of lesion typically presents with degeneration of the acetabular labrum and potential ossification of labral tissue as well as chondral damage on the femoral head/neck. A combined impingement is consistent with both a cam and pincer pathology which can lead to damage of the acetabular labrum and chondral damage on the acetabulum and/or the femoral head/neck. These bony abnormalities can cause and often coincide with capsule, ligament, and muscular dysfunction which often results in abnormal stress and forces through the hip joint. Some examples of concomitant pathologies associated with FAI are anterior inferior iliac spine (AIIS) impingement, iliopsoas impingement, athletic pubalgia, and tearing of the ligamentum teres. Primary hip arthroscopy is utilized to address these potential bony abnormalities, labral and/or chondral damage, and associated soft tissue pathology as needed.

REVISION SURGICAL TECHNIQUE

RHA surgeries of the labrum are focused on restoring the suction-seal mechanism and restoring the biomechanics of the hip joint. This added stability helps decrease the compression forces during hip motion and protects the articular cartilage. In most revision cases, there are adhesions between the labrum and the capsule that need to be addressed at the time of surgery. Whether to repair, augment, or reconstruct the labrum during a RHA depends on the quality of the labral tissue.

If there are minimal adhesions present and the labral quality is good, then any retear or new tear of the labrum can be addressed as in a primary setting. However, in cases of a deficient labrum where a repair is not possible (i.e., hypotrophic labrum, irreparable segmental defect, ossified labrum) then a labral augmentation or labral reconstruction is needed. If circumferential labral fibers are present, then a labral augmentation is preferred to reconstruction as this preserves the innervation of the labrum and the vascularization, which is important for graft healing. In cases where the circumferential labral fibers are not present, a labral reconstruction (either segmental or complete depending on the size of the defect) would be needed. These grafts can be made with either autograft or allograft tissue.

Regardless of the labral surgery performed, any concomitant pathology must also be addressed during the RHA. Most commonly, this would include additional osteoplasty for under-resection in femoroacetabular impingement, a remplissage technique for over-resection for femoroacetabular impingement, addressing chondral defects, lysis of adhesions, or repair or reconstruction of a capsular defect. The remplissage technique utilizes surrounding soft tissue such as the iliobial band (ITB) or Tensor Fascia Latae (TFL) musculature to fill in areas of over-resection, particularly after resection of a cam deformity. The abundant blood supply of the capsulolabral recess predisposes that region to adhesions and in cases of patients with significant adhesions, a "spacer graft" between the labrum and the capsule (similar to an augmentation) may be needed to prevent further adhesions.

POST-OPERATIVE REHABILITATION

Following RHA surgery, the use of a criteria-based progression to advance through rehabilitation phases is proposed and described herein. The criteria-based progression focuses on specific goals to ensure readiness for more progressive loading and flexibility for the revision hip population. Similar to rehabilitation after primary hip arthroscopy, a five phase rehabilitation program is proposed to include: Protection, Endurance, Strength, Power, and Return to Participation/Sport.

PHASE I: PROTECTION

The primary goals of Phase I are protection of healing tissues (bracing, ROM precautions, and load management),
Table 1.

<table>
<thead>
<tr>
<th>ROM restrictions</th>
<th>Revision Hip Arthroscopy (including but not limited to: Labral Repair, Labral Augmentation, Remplissage, Capsular Plication)</th>
<th>RHA +Microfracture</th>
<th>RHA + Gluteus Medius Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hip flexion: No sitting in 90 degrees of flexion x 2 weeks; no active hip flexion</td>
<td>Hip flexion: No sitting in 90 degrees of flexion x 2 weeks; no active hip flexion</td>
<td>Hip flexion: No sitting in 90 degrees of flexion x 2 weeks; no active hip flexion</td>
</tr>
<tr>
<td></td>
<td>Hip Extension - not past neutral x 17 days</td>
<td>Hip Extension - not past neutral x 17 days</td>
<td>Hip Extension - not past neutral x 17 days</td>
</tr>
<tr>
<td></td>
<td>Hip ER - not past neutral x 21 days</td>
<td>Hip ER - not past neutral x 21 days</td>
<td>Hip ER - not past neutral x 21 days</td>
</tr>
<tr>
<td></td>
<td>Hip Abduction - 0-45° x 14 days</td>
<td>Hip Abduction - 0-45° x 14 days</td>
<td>Hip Abduction – 10-30°-45° x 21 days</td>
</tr>
<tr>
<td></td>
<td>Hip Adduction- no restrictions</td>
<td>Hip Adduction- no restrictions</td>
<td>Hip Adduction- no restrictions</td>
</tr>
<tr>
<td></td>
<td>Hip IR- no restrictions</td>
<td>Hip IR- no restrictions</td>
<td>Hip IR- no restrictions</td>
</tr>
<tr>
<td><strong>Brace</strong></td>
<td>17 days</td>
<td>17 days</td>
<td>17 days</td>
</tr>
<tr>
<td><strong>Weightbearing</strong></td>
<td>20lbs x 10-14 days, then wean as appropriate</td>
<td>20lbs x ~ 6 weeks, then wean as appropriate</td>
<td>20lbs x 10-14 days, then wean as appropriate</td>
</tr>
<tr>
<td><strong>Positioning</strong></td>
<td>No prone lying x 4 weeks to avoid stressing anterior capsule</td>
<td>No prone lying x 4 weeks to avoid stressing anterior capsule</td>
<td>No prone lying x 4 weeks to avoid stressing anterior capsule</td>
</tr>
</tbody>
</table>

This table presents common RHA surgical components and frequent restrictions associated with these components.

Symptom management (inflammation and pain), maximize range of motion (ROM) within surgical precautions to reduce adhesion formation, initiate muscle activation, and return to general wellness baselines (sleep, energy, mood, and nutrition).

Surgical restrictions following RHA vary significantly between surgeons and procedures. It is important to ensure surgical precautions are followed as per individual protocol. The range of motion expectations at this point are similar to the typical restrictions seen following primary. Extension and external rotation (ER) are limited to decrease tension on the healing anterior capsule, labral repair, and to protect the incisions. Active hip flexion is also limited to reduce stress of the hip flexor muscles. Weight-bearing during this phase is reduced to protect the repair, and the amount varies with surgeon’s discretion. Compared to a primary labral surgery, the time of restricted weight-bearing may be extended, especially if a micro-fracture is performed. Table 1 portrays some of the frequent surgical restrictions that are seen by the authors. These restrictions are utilized to guide and modify appropriate exercise selection in the early phases of rehabilitation. The restrictions of ROM, positioning, and weight bearing are all incorporated to protect the capsule, reduce stress on the repair, and reduce stress on the joint. Additionally, each of these restrictions and limitations is highly individualized to the patient and particularities of each case and as such, exist on a continuum. Due to the general variability in surgeon preference it is highly encouraged that the progression of range of motion, weight bearing restrictions, and exercise selection is based on post-operative restrictions individualized to each patient.

Symptom management should focus on controlling pain and reducing inflammation. With lengthy revision surgeries, post-operative joint effusion can be a significant issue. This can cause pain and impact muscle activation via arthrogenic and neurogenic inhibition. Manual therapy techniques including lymphatic drainage massage can be used to help manage post-operative swelling. The lymphatic system plays a big role in removing excess interstitial fluid and returning this fluid to the circulatory system. The use of continuous passive motion can help facilitate a pumping action, by creating a sinusoidal oscillation in intra-articular pressure, which will aid in moving blood and edema fluid away from the joint and periarticular tissues.

Following suture removal, scar mobilization can be beneficial to manage pain and to prevent adhesion formation that may impact ROM and pain in later stages. Utilization of passive circumduction is standard for early post-operative care due to its propensity to reduce scar tissue formation. Research has shown there to be a 4.1x increase in scar tissue formation in hips that do not receive circumduction. The use of the medication Losartan has become more common following hip procedures to ameliorate cartilage deficits and reduce postoperative fibrosis via the blocking of transforming growth factor beta-1. Figure 4 shows an early stage exercise to introduce ROM.

The gluteal muscles are essential in pelvic control during gait and single leg stance. Seventy percent of the abductor force required to maintain pelvic stability in the frontal plane is provided by muscles that insert into the greater trochanter. The maximal hip extension ROM achieved during gait is shown to increase the forces on the anterior hip joint. Consequently, general decreases in force output from the gluteal muscles during extension and the iliopsoas muscle during flexion causes an increase in anterior hip joint forces. A solid foundation of good gluteal maximus,
Figure 1. Quadruped Rock Backs. An exercise used to move from a tabletop position to a child’s pose position and then toward a modified plank. Utilized for AROM of the hip within most surgical precautions.

Figure 2. Hip Thrust. Patient is in tall kneeling position at end of table with ankles off of the table for comfort. Patient then sits buttock toward heels, pillow placed for comfort in ROM. Patient then initiates gluteal activation to move into hip extension. A medicine ball can be used for extra dynamic load and core activation.

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medius and minimus muscle activation and control during Phase I is important, before initiating endurance and progressing gait training. Figure 2 is an exercise utilized once weight bearing restrictions are lifted to promote gluteus maximus activation.

There is controversy regarding compensation patterns and movement dysfunction in rehabilitation. Do they cause pain and dysfunction or are they normal variations of human movement? Alternative neuromuscular strategies are commonly observed in individuals with mechanical hip pain and patients post hip arthroscopy. In particular, weakness of gluteus maximus with overactivation of hamstrings and lumbar extensors, weakness of gluteus medius with overactivation of tensor fascia latae are often observed in this population. Additionally, weakness of the deep hip rotators and anterior core is often seen. Individuals undergoing revision surgery have spent months if not years experiencing hip pain, which conform with compensatory movement patterns and hip muscle weakness. Being aware of these patterns is important both for the clinician and the patient. An easy way to incorporate the patient into discerning these compensatory patterns is by using subjective assessment of work or fatigue during a task. This can help to tie in the patient’s attention to movement while also incorporating awareness into their exercises by use of internal feedback.

Exercises commonly used during this phase are geared toward both protecting the repair and gradually reintroducing active hip-based movements, within the restrictions of the surgeon. Table 2 highlights exercises utilized throughout the rehabilitation process. The Phase I column in Table 2 presents suggested exercises with the main focus being correct muscle activation during the exercise, starting with active-assisted and moving to active range of motion as the patient is able to re-establish adequate neuromuscular control. Active hip flexion can commence after two weeks due to tissue healing guidelines. Although commonly perceived as overused in hip pathology, the psoas muscle is important in hip flexion and requires adequate strength to perform daily tasks. Figure 3 portrays the hip roll exercise which is integrated to promote psoas activation. In this figure, the patient is palpating their hip flexor muscles. Based on anatomical location and insertion, activation of the more laterally based muscles would be considered more rectus femoris bias while activation of flexors located more medially would be considered more psoas. Although isolation of the psoas is unlikely, this exercise is used to promote submaximal activation of both a commonly weak and potentially overused muscle in hip pathology.

Located in Figure 4 is a flowchart highlighting criteria to progress between the five phases proposed in this commentary. The criteria to progress to Phase II requires appropriate muscle activation, pelvic control in single limb stance and adequate ROM of the hip necessary to progress gait and perform functional movement tasks in the endurance phase. The ROM criteria are set to allow for ap-
Table 2. Exercise Progressions

<table>
<thead>
<tr>
<th>Exercises</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
<th>Phase IV</th>
<th>Phase V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compound Movements</strong></td>
<td>Cat Cow</td>
<td>Shuttle/TRX® Squat</td>
<td>Lunges</td>
<td>Resisted Single Leg Squat</td>
<td>Agility Ladder</td>
</tr>
<tr>
<td><strong>Quadruped Rock Backs</strong></td>
<td>Weight shifting</td>
<td>Single Leg Squat</td>
<td></td>
<td>Lateral/ Diagonal Agility drills</td>
<td>Multiplanar Movements</td>
</tr>
<tr>
<td><strong>Standing Terminal Knee Extension with Band</strong></td>
<td>Squats</td>
<td>Balance squats</td>
<td>Step Up with Knee Drive</td>
<td></td>
<td>Sport Specific Non-Contact Drills</td>
</tr>
<tr>
<td><strong>Standing Abduction Internal Rotation</strong></td>
<td>Balance</td>
<td>Deadlifts</td>
<td>Box Jumps</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dual task balancing</strong></td>
<td>Lateral Step down</td>
<td>Single Leg Deadlift</td>
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<td></td>
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<tr>
<td><strong>Neurocognitive tasks</strong></td>
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<tr>
<td><strong>Hip Extension</strong></td>
<td>Quadruped Hip Extension</td>
<td>Bird Dogs</td>
<td>Single Leg Bridges</td>
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<tr>
<td><strong>Hip Thrusters</strong></td>
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<tr>
<td><strong>Bridges</strong></td>
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<tr>
<td><strong>Hip Abduction</strong></td>
<td>Standing Hip Abduction Internal Rotation</td>
<td>Sidelying Deep External Rotator (fig. 5)</td>
<td>Hip Hikers</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>External Rotators</strong></td>
<td>Sidelying Glute Holds &amp; Kick</td>
<td>Lateral walking</td>
<td></td>
<td>Hip Hikers with Rotation</td>
<td></td>
</tr>
<tr>
<td><strong>Reverse Clams</strong></td>
<td>Glider Extension/ Abduction</td>
<td></td>
<td></td>
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<tr>
<td><strong>Clam to Neutral</strong></td>
<td>Side planks (with hip abduction)</td>
<td></td>
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</tr>
<tr>
<td><strong>Hip Flexor/Core</strong></td>
<td>Side Lying Hip Flexion Assist</td>
<td>Standing Marches</td>
<td></td>
<td>Full planks</td>
<td></td>
</tr>
<tr>
<td><strong>Hip Rolls (fig. 3)</strong></td>
<td>Resisted Hip Rolls (fig. 3)</td>
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<tr>
<td><strong>Transverse Abdominus Activation</strong></td>
<td>Heel Drag</td>
<td></td>
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<td></td>
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<tr>
<td><strong>Plank (from Knees)</strong></td>
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</tbody>
</table>

This table presents exercise suggestions for the 5 Phases of Rehabilitation suggested in this commentary.

Figure 3. Hip Roll. Patient lays in supine with legs supported on a large ball. Patient then focuses on pulling the ball inward by activating the iliopsoas muscle, anecdotally more medially located. Patient can use hands to palpate muscle activation.
appropriate functional motion with walking and transitional movements such as sit to stand. The ROM expectations for ER and flexion are less than typical surgical restrictions placed upon these motions in early rehabilitation. Prone hip extension, TA activation, and the gluteus medius side lying hold tests allow for assessment of muscle function that is less aggressive than dynamometer testing, which is inappropriate at this stage of healing. These particular tests are chosen to assess for gluteal activation and core stability in early rehabilitation, as they will set the stage for more dynamic strengthening later and their correct performance will determine compensatory patterns that may be present in hamstring, latissimus dorsi, or hip flexor muscle groups. Single leg stance testing is utilized to assess the ability of the lateral hip muscles in achieving a neutral pelvis on one limb, necessary for gait.

PHASE II: ENDURANCE

Phase II, or the endurance phase, focuses on the introduction and improvement of muscular endurance for the ability to perform activities of daily living (ADLs) without pain or dysfunction. These dysfunctions could involve movement deviations and/or compensations. The main goals for this phase are normalizing active ROM (AROM) compared to the non-injured side, building endurance in hip musculature to allow progression to full weight-bearing with a non-analgic gait pattern, and reestablishing tolerance to joint and tissue loading in preparation for future strength exercise progression. Exercises should be provided in an endurance set-rep scheme with three sets of 15-20 repetitions, performed two to three times per week. Continuing to focus on neuromuscular re-education is paramount for the hip revision population in order to deconstruct pre-surgical compensation patterns and promote ideal muscle firing pattern for the hip complex that were established in Phase I. Initiating cardiovascular and work capacity training is also important in this phase.

Following RHA, the flexion, abduction, external rotation (FABER) position can be utilized to slowly integrate functional ER ROM and to reintroduce a previously irritating position. The FABER test is utilized to assess soft tissue restrictions in the anterior hip. Tissue tone or guarding of the psoas can be seen in ER or FABER positioning and may be symptomatic for some patients. Use of gentle contract-relax from proprioceptive neuromuscular facilitation (PNF) concepts can integrate reciprocal inhibition to reduce psoas or TFL guarding. Gentle joint mobilizations are another technique to help neuro-modulate the hip joint following revision surgery. Ensuring a restriction is capsular as opposed to bony should be established before utilizing higher grade mobilizations in this population. Assessing inter-
nal and external rotation ROM both in positions of capsular tightness and muscle tension (hip extension versus hip flexion) should help to determine discrepancies in motion that would bias capsular restriction versus ROM restriction. Manual therapy techniques can be utilized in the neuromuscular re-education process to address muscle hypertonicity, pain, and dysfunction. Pain and tone in the adductors, psoas and TFL can be present and may affect progress in this phase of post-operative rehabilitation if overlooked.

Normalizing gait to ensure functional ambulation for the patient to return to typical ADLs is essential during this phase. When progressing weight-bearing, respecting surgical precautions and gradually reintroducing weight to the joint is paramount. The use of scales is common to incrementally introduce a percent of body weight while using crutches to desensitize the joint to external forces. Slow progression from two crutches to one crutch over multiple weeks may be necessary to avoid rebound inflammation, pain, and gait dysfunction. The use of pool walking, aquatic treadmills, Alter-G treadmills, and the TRX® can be used to systematically increase load on the joint. This, in particular with hip revision cases, is important to allow the joint adequate and individualized time to adjust to body weight. Patience during this phase can be the difference between appropriately training the hip complex muscles to accept load during functional activities and perpetuating long-standing compensatory patterns. It is paramount that criteria-based progression be used in gait training versus time-based progression due to the variability in crutch weaning time.

During this stage, integration of neurocognitive challenges to single leg balance, lateral and posterior hip strengthening progression, and deep rotator strengthening is valuable. Refer to Table 2 for the exercises included in this phase. Resistance should be added to open kinetic chain exercises and once adequate lower extremity strength and proximal stability has been restored the addition of closed kinetic chain exercises should be introduced. This will prepare the hip joint to accept heavier loads in the later phases. Additionally, monitoring the degree and location of fatigue as well as undesirable signs and symptoms of overuse during a task can help to prevent delays in recovery and symptom exacerbation.

A key point of Phase II is returning to performing ADLs. Educating patients on how to best micro-dose their ADLs to promote function and minimize micro-inflammation during this phase is crucial for hip revision patients, who often cannot tolerate even minimal activity. This particular point can be guided by subjective symptoms or fatigue. Significant education regarding spacing activities over the course of a day or over multiple days rather than performing the entirety of a task is encouraged. The goal is to minimize micro-inflammation which can cause arthrogenic inhibition, while progressing capacity for load tolerance. Gaining independence with ADLs and gait can be a big accomplishment for RHA patients and achieving this milestone should be acknowledged. However, further advancement and new goals should be made. It is important they continue to progress with strengthening in order to create healthy habits and increase their chances of preserving their hip function. An in vivo study by Bergmann et. al.52 showed that the average person loaded their hip joint at 238% body weight while walking at 4km/h, 251% with climbing stairs, and 260% with descending stairs. Giarmatizis et. al.53 and Lue-pongsak et. al.54 have shown that changes in gait speed and running can increase hip joint forces. Achieving superior strength is important in dissipating these forces and maximizing long term outcomes following RHA surgeries and will be addressed in the next phase.

Refer to Figure 4 for the criteria for progression from this phase. These tests aim to ensure adequate muscular strength in the gluteal complex and hip flexor muscles. All isometric testing is done utilizing hand held dynamometry (preferred) or by achieving a 4 strength grade using manual muscle testing in standard positions. The lateral trunk endurance test is a reliable and valid measure to assess core stability, pictured in Figure 5.55 The anterior reach of the Y-Balance test has been shown to have predictive validity for injury occurrence across adults and athletes alike, particularly if side-to-side discrepancy is >4cm. However, these studies are not specific to the hip population.56,57 In the authors’ opinion, at this stage of rehabilitation a < 8cm difference is utilized as an achievable measurement to begin assessing symmetry in dynamic balance, and this will be progressed upon in the next phase. All of these components set the stage for strengthening, by establishing an adequate muscular base of strength, endurance, and neuromuscular control.

PHASE III: STRENGTHENING

The strength phase, or Phase III, focuses on increasing load and building strength in the muscles of the lower extremity and core. At this stage of rehabilitation, exercise prescription should be changed according to strength parameters. Exercises should be performed in 3–6 sets of 3–5 repetitions at a higher load, 60–80% of one rep maximum for novice to experienced individuals respectively.59 Table 3 ranks exercises based on percentage of maximum voluntary isometric contraction (%MVIC) for gluteus maximus and gluteus medius strengthening, and it is recommended they are included in this phase of rehabilitation. Neuromuscular activation of 40–60% MVIC is recommended as a minimum for a strengthening effect59 while around 70% MVIC is thought to elicit an optimal strengthening effect and achieve desired adaptations in muscle morphology, such as hypertrophy.58 However, the use of 1RM can be difficult and potentially unsafe to achieve and assess in the rehabilitative setting. In a recent meta-analysis by Lea et al., rate of perceived exertion (RPE) has been shown to be a valid measure of exercise intensity and exertion.60 As such, utilizing RPE can be monitored to ensure sufficient load is being applied. Considering this information, a 60–80% intensity of 1RM can be estimated at about 6–8/10 or 14–17/20 using an RPE scale.60 Introduction of rate of force development (RFD) during these exercises in the later stages of Phase III can help build confidence with moving faster and without fear. Utilizing speed in exercise tasks can promote this RFD bias. RFD correlates to maximum vol-
Figure 5. Lateral Trunk Endurance Test. The patient starts in a side-lying position and begins by pushing up onto the elbow and, ideally, the foot until the body is elevated off of the table. This is also the same positioning for the side plank with hip abduction (a therapeutic exercise). As this exercise becomes less difficult, the top leg can be elevated as well to promote bilateral hip abductor activation and increased challenge to core stability.

Table 3. MVIC of Gluteus Medius and Gluteus Maximus During Common Therapeutic Exercises

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Gluteus Medius - MVIC%</th>
<th>Gluteus Maximus - MVIC%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boren</td>
<td>Distefano</td>
</tr>
<tr>
<td>Quadruped hip ext (moving limb)</td>
<td>22.03</td>
<td>40 ± 38 (30° hip flex)</td>
</tr>
<tr>
<td>Clamshell (45° hip flexion)</td>
<td>47.23</td>
<td>38 ± 29 (60° hip flex)</td>
</tr>
<tr>
<td>Single leg deadlift</td>
<td>56.08</td>
<td>58 ± 25</td>
</tr>
<tr>
<td>Side-lying hip abduction</td>
<td>62.91</td>
<td>81 ± 42</td>
</tr>
<tr>
<td>Reverse clamshell (hip ext to 0° + hip abd to neutral)</td>
<td>76.88</td>
<td></td>
</tr>
<tr>
<td>*Single leg squat</td>
<td>82.26</td>
<td>64 ± 24</td>
</tr>
<tr>
<td>*Side plank (ipsilateral)</td>
<td>106.22</td>
<td></td>
</tr>
</tbody>
</table>

Exercises listed with their respective MVIC for both gluteus medius and maximus
Abbreviation: MVIC - maximum voluntary isometric contraction
* indicates MVIC >70% in both GMED and GMAX, according to Boren et al.58

By improving the RFD in this phase, it helps to set the stage for power training in phase IV.

The criteria for progression to Phase IV are referenced in Figure 4. Achieving adequate strength of the muscles of the hip complex, compared to the non-injured limb (limb symmetry index), to assess muscular function is important to prepare for the power phase. Maximized strengthening of both internal and external rotator muscle groups is important in the homeostasis of the hip, with particular research supporting the deep external rotators, although a specific ratio has not been confirmed. Tateuchi et al.61 showed in-
Figure 6. Sidelying Deep External Rotator. The figure depicts a strengthening exercise utilized to target the deep external rotators of the hip. The starting position has the target leg on the bottom with leg in line with trunk. Squeeze the deep buttock region to initiate the movement of the target foot off of the table in a rotary motion generated at the hip. Cue patient to keep the bottom knee in contact with the table for entire exercise to reduce adductor muscle bias.

Figure 7. Hip Hiker with Rotation. Subject stands near a wall with a large ball placed between hip and wall, maintaining constant pressure. Hinge trunk forward about 45 degrees and extend leg in line with trunk. Patient then rotates pelvis off of the stance leg (working leg) trying to keep trunk, pelvis, and opposite leg in line and moving as one unit.

Examples of exercises for these muscle groups are seen in Figures 6 and 7.

The side plank with hip abduction (Figure 5) is shown to have the highest studied gluteus medius recruitment (103% MVIC). As such, utilization of the side plank with hip abduction test allows good understanding of the patient’s ability to recruit the gluteus medius which has direct impact on ambulation and more advanced activities such as running and jumping. Upon completion, this phase should allow for significant functional improvements and a return to low intensity exercise and functional tasks without pain or dysfunction.

PHASE IV: POWER

Phase IV, or the power phase, is the last required phase before fully allowing patients to return to light impact-based activity. Continuing into this phase is highly dependent on three factors: (1) number of hip surgeries &
revisions, (2) patient expectations, and (3) surgeon expectations. These three factors will help to determine the necessity to progress to a power-based phase and to plan for appropriate expectations following RHA surgery. Should all three of these factors align and Phase III criteria have been met, it is anticipated the individual will have established good neuromuscular control, adequate strength, and the ability for the hip joint and surrounding tissue to accept load without exacerbation of hip pain.

In the author’s experience, in cases of multiple revision surgeries the history of muscular inhibition and compensatory patterns, aberrant joint loading, and the psychosocial factors increase the difficulty in returning to high level activities, and as such expectations should be modified. Presence of joint line space <2mm has been shown to have poor longevity after RHA and a higher probability of total hip arthroplasty/replacement in the future.64,65 Discussion with the medical team regarding joint space narrowing and history of microfracture may be a valuable tool in deciding whether return to higher intensity activities is advisable.64,65 Additionally, psychological readiness scales can be utilized to assess patient’s expectation and to help clinicians in making appropriate and informed decision regarding to sport and participation in later stages of rehabilitation.66 Similar to the earlier phases, the exercise prescription in this phase should also change in conjunction with normal power guidelines.49 Exercises are performed under light to moderate loads, with a prescription of 3 sets of 3-6 repetitions and an emphasis on rate of force development. Power exercises should be scheduled 2-3 times per week and within a session, performed before strength exercises.49

Power exercises apply the maximum amount of force as fast as possible on the basis that force times velocity equals power.49 This training can take many shapes, but during rehabilitation it is important to start slowly and gradually increase speed and load. Plyometric exercises are often a good starting point and can be easily modified to accommodate patient anxiety. Plyometric progression should start with double leg exercises that minimize impact such as use of a shuttle press or TRX® system which can promote a lengthened amortization phase initially and gradually challenge speed as patient comfort and mechanics improve. As tolerance improves, challenging overall load by increasing external resistance and then progressing to jump-down landings can be utilized for improving power. Sagittal plane jumping movements are progressed to frontal and multiplanar movements. Once adequate tolerance to double leg jumping is established without concern, progression to single leg loading such as single leg bounding or hopping can be incorporated. It is necessary to have established good control in jumping at or above full body weight prior to progressing to bounding or hopping. Continued strengthening is important in this phase, and increasing load as tolerated can be an efficient way to increase power.49

Figure 1 shows the progression criteria for the Power Phase. Unique to this progression are components of the Vail Hip Sports Test (VHST) which utilizes testing components that attempt to load the hip in typical impingement angles to assess overall tissue load tolerance and movement patterns.67,68 The four test components include: single knee bend, lateral agility test, diagonal agility test and forward lunge onto box test.67 Additionally, performance on the VHST has been shown to be correlated with hip extension and external rotation strength.68 Triple hop and vertical hop tests have both been shown to be reliable tests following ACL reconstruction and can be adapted for other lower extremity conditions.69 Hop tests are convenient and reproducible in most clinical settings for discerning power differences between lower extremities.69

RETURN TO SPORT

Progression to this phase is individual and highly variable in this patient population. This decision is based on prior history, complexity of surgical procedure, recommendation of surgeon and team, and personal goals of the patient. If performed strategically, this phase can be very attainable despite revision status. In the case of clearance from the full medical team, the suggestion is to ensure greater than or equal to 90% limb symmetry index (LSI) in strength testing and power testing, as outlined in the previous Phases. The agility T-test is added due to its validity and reliable in assessing lower extremity speed, leg power, and agility.70 The agility T-test, strength LSI, power LSI, quality of motion during these tests along with clinical decision making by the health care team will help ensure safe return to sport following hip labral revision surgery. Communication with the patient, coaching staff, medical staff, and strength coaches should be utilized to establish a smooth transition of both load and sport specific training. Ideally, slow integration of sport-specific exercises should be introduced into late stage rehabilitation and increasing difficulty implemented as mastery is achieved. A general guideline should start with sport-specific tasks in isolation, non-contact drills, contact drills, scrimmage or practice situations, and eventually a return to unrestricted competition. Full description of the return to sport phase is beyond the focus of this commentary.

PSYCHOLOGICAL CONSIDERATIONS

Dick, et al. and Chang et al. show a strong correlation between mental health and hip pathology.71,72 Evidence suggests that history or presence of mental health issues negatively impacts outcomes following FAI surgery.71,72 Presence or history of mental illness may have contributed to previous failed hip labral procedures, and although it cannot be assumed as a reason for failure, it may be a contributing factor in the rehabilitation process. Additionally, Dick et al., and Cheng et al. show that consideration for the presence of mental health issues following hip labral repair may prepare the clinician for the potential presence of persistent pain in both early and late rehabilitation postoperatively.71,73 Browning and colleagues showed that patients with pain catastrophizing and kinesiophobia following arthroscopic hip surgery had poor RTS outcomes at one year.74 The use of psychological readiness scales throughout rehab may help to assess areas of fear avoidance or anxi-
iety regarding RHA rehabilitation and return to prior levels of function. Recently, the Hip-RSI, a modified version of the ACL-RSI, has been proven to be both valid and reliable in assessing psychological readiness following hip arthroscopy.66 The Short Form-36 and Tampa Scale of Kinesiophobia66,75,76 are additional options to evaluate fear of motion, although not specific to post-operative hip surgery.77 In addition to the use of validated outcome measures, the incorporation of pain neuroscience education may be helpful in addressing and assuaging fears and habits that may negatively impact rehabilitation.

Another component of rehabilitation for the RHA patient is the importance of self-efficacy.73 Albert Bandura defined self-efficacy as the perception of one’s ability to succeed in a specific situation. Jochimsen et al.73 found that poor self-efficacy has been shown to correlate with higher pain levels. There is evidence that also suggests that high self-efficacy can improve adherence to a program, improve physical function, and decrease pain.73,78 Thus, as healthcare workers utilizing discussion of vicarious experiences, persuasion, and even positive reinforcement to maximize a patient’s perception of efficacy during their rehabilitation may be important. The referral to a psychologist can be an invaluable tool to address any psychological concerns present throughout rehabilitation.

CONCLUSION

When considering the typical difficulties that those who undergo RHA experience, the proposed criteria-based progression allows for patient individualization throughout the course of therapy. With a history of multiple hip labral surgeries, the timeline for recovery may lengthen and vary based on the complications that may be present. By removing the time-based criteria traditionally seen post-operatively, and utilizing a criteria-based progression, we can assist patients to be better equipped to achieve the motion, strength, stability, power, and function for returning to their maximum potential. The criteria proposed in this commentary is a working guideline to encourage the clinician to perform regular assessment of motion, endurance, strength, and power as tissue healing occurs and progress based upon suggested criterion.

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REFERENCES


**Graft-Specific Surgical and Rehabilitation Considerations for Anterior Cruciate Ligament Reconstruction with the Quadriceps Tendon Autograft**

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1 Physical Therapy, Training HAUS, 2 Physical Therapy, Twin Cities Orthopedics, 3 Orthopedics, Twin Cities Orthopedics

Keywords: anterior cruciate ligament reconstruction, autograft, physical therapy, quadriceps tendon autograft, rehabilitation

Anterior cruciate ligament reconstruction (ACLR) with a bone-patellar tendon-bone (BPTB) or hamstring tendon (HT) autograft has traditionally been the preferred surgical treatment for patients returning to Level 1 sports. More recently, international utilization of the quadriceps tendon (QT) autograft for primary and revision ACLR has increased in popularity. Recent literature suggests that ACLR with the QT may yield less donor site morbidity than the BPTB and better patient-reported outcomes than the HT. Additionally, anatomic and biomechanical studies have highlighted the robust properties of the QT itself, with superior levels of collagen density, length, size, and load-to-failure strength compared to the BPTB. Although previous literature has described rehabilitation considerations for the BPTB and HT autografts, there is less published with respect to the QT. Given the known impact of the various ACLR surgical techniques on postoperative rehabilitation, the purpose of this clinical commentary is to present the procedure-specific surgical and rehabilitation considerations for ACLR with the QT, as well as further highlight the need for procedure-specific rehabilitation strategies after ACLR by comparing the QT to the BPTB and HT autografts.

**Level of Evidence**

Level 5

INTRODUCTION

Rupture of the anterior cruciate ligament is a well-known sports injury, with a higher injury incidence in females and those who participate in Level 1 sports.1–4 Traditionally, anterior cruciate ligament reconstruction (ACLR) with a bone-patellar tendon-bone (BPTB) or hamstring tendon (HT) autograft has been the preferred surgical procedure for managing complete tears of the anterior cruciate ligament, with a surgeon-preference towards the BPTB as the standard of care.5–9 Recently, international utilization of the quadriceps tendon (QT) autograft for primary and revision ACLR has increased in popularity;10–13 ACLR with the QT may yield less graft harvest site morbidity than the BPTB and better patient-reported outcomes than the HT.14–16 However, revision ACLR outcomes from the Danish Knee Ligament Reconstruction Registry suggests higher graft laxity and failure rates when performing primary ACLR with the QT than both the BPTB and HT;17 these findings have been debated,18,19 along with other literature reporting similar graft survivorship between the QT, BPTB, and HT.14–16,20

Justifying the increased utilization of the QT for ACLR, anatomic and biomechanical studies have highlighted the robust properties of the QT itself, with superior levels of collagen density, length, size and load-to-failure strength than the BPTB.21–25 However, due to the multiple muscular origins of the quadriceps tendon, the QT has the potential for more variation in laminar structure and fiber orientation than the BPTB and HT.26–28 This non-uniformity of the quadriceps tendon, along with variation in surgeon skill and reconstruction technique, has been suggested as a rea-
son for the higher QT failure rates within the Danish Knee Ligament Reconstruction Registry. They observed that higher QT failure rates within the Danish Knee Ligament Reconstruction Registry, 17-19

In addition to intra-graft characteristics, graft-specific considerations for ACLR should also include fixation technique, management of the graft harvest site and the overall graft ligamentization process. For example, graft fixation with an interference screw may facilitate better graft incorporation than suspension fixation and reduce the incidence of bone tunnel widening.29-31 Regarding the graft harvest site, ACLR with the QT and BPTB may produce more postoperative quadriceps weakness than the HT,34,32-34 whereas a higher incidence of kneeling-related knee pain has been reported with the BPTB than both the QT and HT autografts.34,35 Lastly, the bone-to-bone healing of the BPTB within the bone tunnels facilitates graft osteointegration, which is a more efficient incorporation process than the fibrovascular healing of an all soft-tissue graft.36 These considerations influence surgical decision-making and the rehabilitation plan-of-care, to which the rehabilitation specialist must tailor their exercise prescription in an effort to optimize outcomes after ACLR.

Although previous literature has described rehabilitation considerations for the BPTB and HT autografts, 28,36-39 there is less published with respect to the QT.39-41 Therefore, the purpose of this clinical commentary is to present the graft-specific surgical and rehabilitation considerations for ACLR with the QT, as well as further highlight the need for graft-specific rehabilitation strategies after ACLR by comparing the QT to the BPTB and HT autografts.

ANATOMIC AND BIOMECHANICAL CONSIDERATIONS

The quadriceps and hamstring tendons are different than the patellar tendon in their innate function to connect muscle-to-bone, whereas the patellar tendon connects bone-to-bone. Considering this, differences in stiffness and elastic properties are known to exist between autograft tissue used for ACLR,42-44 with the quadriceps tendon producing more absolute stiffness than both the patellar and semitendinosus tendons but a lower elastic modulus and relative strain tolerance than the patellar tendon.44,45 (Table 1).

While these findings reflect total-graft biomechanical properties, previous work has highlighted the fact that regional variation in tendon elasticity and stiffness may also exist; the tendon region closest to the myotendinous junction is less stiff than the tendon region adjacent to the enthesis.48 This is an important consideration, as biomechanically-induced graft failure studies have reported a difference in failure location for the QT harvested with a patellar bone block (B-QT) than that of the BPTB and multiple-strand HT autografts; failure of the B-QT was most common at the bone-tendon interface,44 whereas universal stretch/mid-substance failures have been reported with the all soft-tissue QT (S-QT), BPTB and multiple-strand HT.44,45-47 These observations suggest the B-QT has more within-graft variation in regional elasticity and structure, creating increased stress at the bone-tendon interface and the observed graft failure-location.26,44-49

Compared to the HT and BPTB, more variation in lamar structure is present with the QT. In contrast to the continuous structure of the hamstring and patellar tendons, the quadriceps tendon is typically described as a common tendon with a three-layered arrangement; a superficial layer derived from rectus femoris, an intermediate layer from vastus medialis and vastus lateralis, and a deep layer from vastus intermedius.26-28 Although the extent to which lamellar structure contributes to graft fixation pull-through is unknown, a biomechanical study by Arakagi et al.50 reported significant suspensory fixation pull-through with a 150-newton load on the S-QT relative to a bone-block control.

GRAFT COMPOSITION AND HARVESTING TECHNIQUE CONSIDERATIONS

The harvesting technique of the QT can vary, and along with this, different rehabilitation considerations for graft composition are warranted. The B-QT facilitates partial graft osteointegration as early as 4-6 weeks after ACLR through the bone-to-bone healing of the single bone block within the bone tunnel,51,52 but likewise, carries a 1.4-8.8% risk of patellar fracture due to bone block harvest.53-55 Conversely, the S-QT is harvested without a patellar bone block and mitigates the risk of patellar fracture,56 but will take a minimum of 10 to 12-weeks for the fibrovascular interface to form between the S-QT and the bone tunnels.28,56-58 This between-graft difference in integration, in conjunction with the findings of Arakagi et al.50 suggests accelerated rehabilitation approaches may be less appropriate for the S-QT fixated with suspensory fixation, especially as graft tension is highly dependent on fixation until biological integration of the graft within the bone tunnels has occurred. While this is an extrapolated suggestion, short-term increases in graft laxity have been reported with the early introduction of open-kinetic-chain (OKC) quadriceps resistance training after ACLR, to which slightly increased levels of graft laxity were reported with the HT relative to the BPTB when OKC quadriceps resistance training with distal tibial load was initiated between 0-45 degrees of knee flexion weeks 6-12 after ACLR.59

The theoretical advantage of graft osteointegration with the B-QT is not currently supported by the literature.28,56-58 Specifically, a higher incidence of postoperative rotatory instability (16% vs 0%) and atraumatic graft ruptures (24% vs 0%) have been observed after ACLR with the B-QT compared to the S-QT;54 these findings suggest ACLR with the S-QT may yield better postoperative stability than the B-QT. However, evidence is still limited,54 and the full-thickness B-QT appears to be more biomechanically similar to the BPTB than the S-QT, as well as may better replicate the tissue properties of the native anterior cruciate ligament44,46 (Table 1). Lastly, ACLR with the S-QT may not provide adequate quadriceps tendon graft-length in some populations,60 especially women,61 and cosmetic...
retraction of the rectus femoris is a known complication related to proximal QT harvest.28,53,55

Outcomes comparing the full-thickness QT (F-QT) to the partial-thickness QT (P-QT) are limited with only one direct comparison published within the literature.62 QT thickness does not appear to influence donor site pain, failure rates or patient-reported outcomes.63 However, the biomechanical properties of the P-QT appear to be less robust than the F-QT (Table 1).

The F-QT produces a larger diameter graft and causes deeper disruption of the tissue at the graft harvest site. With this, violation of the suprapatellar pouch with F-QT harvest can produce a suprapatellar hematoma,55 which is a known complication after ACLR with the F-QT.40 More postoperative quadriceps inhibition may also be theorized with the F-QT relative to the P-QT, as full-thickness quadriceps tendon harvest will disrupt the lamellar layers associated with the vastus medialis, vastus lateralis and vastus intermedius.56,27,64 Along with the inevitable increase in suprapatellar scarring, the high collagen density and graft-specific stiffness of the QT are suggested reasons for the observed incidence of arthrofibrosis after ACLR with the QT,20,40,65,66 to the which the F-QT may exacerbate.67

### Table 1. Biomechanical characteristics of the native anterior cruciate ligament and common autografts used for anterior cruciate ligament reconstruction

<table>
<thead>
<tr>
<th>Graft Type</th>
<th>Cross-Sectional Area (mm²)</th>
<th>Maximal Load To Failure (N)</th>
<th>Ultimate Stiffness (N/mm)</th>
<th>Ultimate Stress (N/mm²)</th>
<th>Ultimate Strain (%)</th>
<th>Common Failure Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native ACL</td>
<td>44</td>
<td>2160</td>
<td>242</td>
<td>49</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>BPTB Autograft†#</td>
<td>48</td>
<td>1580-1810</td>
<td>278-324</td>
<td>69.9</td>
<td>14</td>
<td>Deep Layer of Patellar Interface / Femoral Origin / Mid-substance</td>
</tr>
<tr>
<td>HT Autograft†§#</td>
<td>11</td>
<td>1060 (1-Stand)</td>
<td>213 (1-Stand)</td>
<td>99 (1-Stand)</td>
<td>11.6 (4-stand)</td>
<td>Mid-Substance / Universal Stretch</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>2330 (2-stand)</td>
<td>469 (2-stand)</td>
<td>100 (2-stand)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1750 (4-stand)</td>
<td>433 (4-stand)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-QT†# (Full Thickness)</td>
<td>91</td>
<td>1450-2186</td>
<td>370-466</td>
<td>49</td>
<td>11.2</td>
<td>Bone-Tendon Interface</td>
</tr>
<tr>
<td>S-QT# (Full Thickness)</td>
<td></td>
<td>1260</td>
<td>257</td>
<td></td>
<td></td>
<td>Proximal Graft / Universal Stretch</td>
</tr>
<tr>
<td>S-QT# (Partial Thickness)</td>
<td></td>
<td>972</td>
<td>228</td>
<td></td>
<td></td>
<td>Distal Graft / Universal Stretch</td>
</tr>
</tbody>
</table>

ACL; anterior cruciate ligament, BPTB; bone-patellar tendon-bone, HT; hamstring tendon, B-QT; quadriceps tendon with a patellar bone block; S-QT, all soft-tissue quadriceps tendon; † includes data from Woo et al;‡ includes data from Shani et al;§ includes data from Hamner et al;¶ includes data from Schilaty et al; † includes data from Strauss et al; †§ includes data from Magnusson et al.

### EXTENSOR MECHANISM CONSIDERATIONS

Harvesting the P-QT may reduce the tensile strength of the quadriceps tendon by as much as 34%, which is greater than the 25% reduction in patellar tendon strength after BPTB harvest.23 These findings have implications for rehabilitation, as greater impairments in quadriceps strength have been observed after ACLR with the QT and BPTB than with the HT.14,32–34,68 Following QT harvest, reduced quadriceps activation and strength may initially create a more protective healing environment at the graft harvest site. However, long-term reductions in quadriceps strength are detrimental to knee function and are one of the reasons why it may take longer to achieve performance testing milestones after ACLR with the QT and BPTB than with the HT.33,38,39,68

Considering P-QT harvest reduces the tensile strength of the quadriceps tendon by more than a third,23 a greater initial reduction in quadriceps strength may be expected after ACLR with the QT compared to the BPTB and HT.58 Quadriceps weakness from extensor mechanism graft harvest appears most extreme during the first three months after ACLR,68 suggesting any difference in quadriceps strength between ACLR with the QT and BPTB may only be distinguishable during the first three to four months after.
ACLR\textsuperscript{34,68}; this suggestion is supported by the fact quadriceps strength is not statistically different between the QT and the BPTB at six to 24 month follow-up.\textsuperscript{34,68,69}

**REHABILITATION CONSIDERATIONS**

**EARLY PHASE (POSTOPERATIVE WEEKS 0–8)**

After ACLR with the QT, the graft’s composition and fixation method should be communicated to the rehabilitation specialist, as these factors dictate the overall graft ligation process\textsuperscript{35,70–72}; the amount of tissue trauma at the graft harvest site\textsuperscript{44}; and the durability of the graft-bone tunnel construct.\textsuperscript{29–31,50,75} ACLR with the F-QT carries the risk of developing a suprapatellar hematoma\textsuperscript{55,63}; pain and focal swelling at the graft harvest site is indicative of a hematoma and should be differentiated from a postoperative knee effusion.\textsuperscript{41} If a suprapatellar hematoma is identified, the surgical team should be notified as physician follow-up may be indicated.

The early restoration of passive knee extension is a crucial component of rehabilitation after ACLR, regardless of graft type.\textsuperscript{74} ACLR with the QT may carry an elevated risk of postoperative stiffness due to the larger graft size,\textsuperscript{67} presence of suprapatellar scarring and ongoing quadriiceps inhibition.\textsuperscript{20,40,65,66} Interventions to improve patellar mobility, knee range-of-motion and soft tissue compliance should be implemented immediately after surgery. Failure to restore passive knee extension by postoperative week eight may indicate the need for a subsequent lysis-of-adhesions procedure.\textsuperscript{20,65}

Like the BPTB, ACLR with the QT requires an isolated quadriiceps training load-progression to be a cornerstone of the rehabilitation program.\textsuperscript{35,34,75,76} Early phase quadriiceps rehabilitation should include quadriiceps setting and other activation exercises into terminal knee extension (TKE), with the goal of restoring active knee extension as soon as possible (Table 2). The early implementation of neuromuscular electrical stimulation and/or blood flow restriction during quadriiceps exercise may improve neuromuscular recruitment and help mitigate thigh muscle atrophy,\textsuperscript{77–80} as well as facilitate improvements in muscle size and strength throughout rehabilitation.\textsuperscript{81–83} The quadriiceps muscle load-progression should start with quadriiceps setting and straight-leg raises in non-weightbearing, and progress onto closed-kinetic-chain (CKC) positions which emphasize the restoration of knee control in weightbearing (Table 2).\textsuperscript{84} The CKC quadriiceps load-progression should begin with the double-leg squat exercise and incorporate body-weight isometric and isotonic contractions in low levels of knee flexion (Figure 1A) (Table 2).\textsuperscript{85}

Graft osteointegration with the B-QT supports the implementation of an accelerated resistance training approach within the first 4–6 weeks after ACLR,\textsuperscript{59} such as OKC quadriiceps resistance training with distal tibial load between 0–45 degrees of knee flexion\textsuperscript{86}; the combined utilization of the B-QT with interference screw fixation may further justify this clinical decision\textsuperscript{29–31,44,50,70,71,87} (Table 3). The S-QT fixed with suspensory fixation may warrant a more traditional approach to resistance training the first 10–12 weeks after ACLR\textsuperscript{59,72,73,87,88} (Table 2); healing time is needed to mitigate the risk of fixation slippage,\textsuperscript{50,75,85,89} graft laxity and bone tunnel widening with an all soft-tissue graft,\textsuperscript{17,29–31,50} as well as facilitate optimal fibrovascular integration of the graft within the bone tunnels\textsuperscript{72,87,89–93} (Table 3).

**MIDDLE PHASE (POSTOPERATIVE WEEKS 8–16)**

As goals related to joint homeostasis are achieved, the focus of rehabilitation transitions from resolving impairments in muscle activation and knee range-of-motion, to rebuilding the surgical limb’s functional capacity to manage load. Ongoing quadriiceps weakness is expected after ACLR with the QT,\textsuperscript{14,15,33,34,75} and knee-specific load-progressions should be designed to best-manage the graft harvest site while stimulating improvements in quadriiceps size and strength. Prior research has highlighted associations between knee position and extensor mechanism biomechanics,\textsuperscript{94–96} from which the quadriiceps training load-progressions can be derived (Table 2).

As the knee moves into deeper knee flexion, preferential loading of the quadriiceps tendon increases relative to the patellar tendon.\textsuperscript{94} This load-transition is the result of an improving patellar tendon mechanical advantage with a concurrent increase in passive tension within the quadriiceps.\textsuperscript{94,95} Considering the laminar structure of the quadriiceps tendon, variations in quadriiceps length-tension can predispose the quadriiceps tendon to greater levels of shear/compressive load, as well as non-uniform intratendinous...
<table>
<thead>
<tr>
<th>Postoperative Month</th>
<th>Single-Leg Progression</th>
<th>Split-Squat Progression</th>
<th>Open-Kinetic-Chain Progression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month 0-1</td>
<td>Banded TKE (Sitting at Edge of Surface)</td>
<td>Quadriceps Setting (Straight Leg Raise)</td>
<td>Short/Long-Arc Quad (AROM)</td>
</tr>
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<td>Prescription Type: Neuromuscular Reeducation and Muscle Activation</td>
<td>Prescription Type: Neuromuscular Reeducation and Muscle Activation</td>
</tr>
<tr>
<td></td>
<td>F: 3-4 times/day</td>
<td></td>
<td>F: 3-4 times/day</td>
</tr>
<tr>
<td></td>
<td>I: Elastic resistance band exercise (light to heavy)</td>
<td></td>
<td>I: Weight of lower leg</td>
</tr>
<tr>
<td></td>
<td>T: Isotonic (concentric/eccentric phase)</td>
<td></td>
<td>T: Isotonic (concentric/eccentric phase)</td>
</tr>
<tr>
<td></td>
<td>T: 10-15 minutes each exposure</td>
<td></td>
<td>T: 10-15 minutes each exposure</td>
</tr>
<tr>
<td></td>
<td>V: 2-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE</td>
<td></td>
<td>V: 2-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE</td>
</tr>
<tr>
<td></td>
<td>P: Progression of elastic resistance band level; superimposition of NMES with exercise; progression onto blood flow restriction exercise (1-2 times/day, 3-4 set to volitional fatigue at 80% LOP)</td>
<td></td>
<td>P: Progression of body position and/or onto the straight leg raise exercise (with/without external resistance at the ankle); superimposition of NMES with exercise; progression onto blood flow restriction exercise (1-2 exposures/day, 3-4 set to volitional fatigue at 80% LOP)</td>
</tr>
<tr>
<td>Month 1-2</td>
<td>Banded TKE (Standing)</td>
<td>Double-Leg Squat (0-60 Degrees of Knee Flexion)</td>
<td>Long-Arc Quad (AROM with Blood Flow Restriction)</td>
</tr>
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<td></td>
<td>Prescription Type: Neuromuscular Reeducation and Muscle Activation</td>
<td>Prescription Type: Neuromuscular Reeducation and Muscle Activation</td>
<td>Prescription Type: Cell Swelling/Atrophy Mitigation/Hypertrophy</td>
</tr>
<tr>
<td></td>
<td>F: 2-3 times/day</td>
<td></td>
<td>F: 1-2 times/day</td>
</tr>
<tr>
<td></td>
<td>I: Elastic resistance band (light to heavy)</td>
<td></td>
<td>I: Weight of lower leg, blood flow restriction at 80% LOP</td>
</tr>
<tr>
<td></td>
<td>T: Isotonic (concentric/eccentric phase)</td>
<td></td>
<td>T: Isotonic (concentric/eccentric phase)</td>
</tr>
<tr>
<td></td>
<td>T: 10-15 minutes each exposure</td>
<td></td>
<td>T: 10-20 minutes each exposure</td>
</tr>
<tr>
<td></td>
<td>V: 3-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE</td>
<td></td>
<td>V: 3-4 sets to volitional fatigue</td>
</tr>
<tr>
<td></td>
<td>P: Progression of elastic resistance band level; progression onto blood flow restriction exercise (1-2 times/day, 3-4 set to volitional fatigue at 80% LOP)</td>
<td></td>
<td>P: Addition of progressive isometric contractions at 45-90 degrees of knee flexion with/without the superimposition of NMES</td>
</tr>
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</table>

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<table>
<thead>
<tr>
<th>Postoperative Month</th>
<th>Single-Leg Progression</th>
<th>Split-Squat Progression</th>
<th>Open-Kinetic-Chain Progression</th>
</tr>
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<tbody>
<tr>
<td><strong>Month 2-3</strong></td>
<td><strong>Double-Leg Wall Squat (60-90+ Degrees of Knee Flexion)</strong></td>
<td><strong>Split-Squat (0-60 Degrees of Knee Flexion)</strong></td>
<td><strong>Knee Extension Machine (Single-Leg with Blood Flow Restriction)</strong></td>
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<tr>
<td></td>
<td><strong>Prescription Type:</strong> Extensor Mechanism Load-Tolerance/Hypertrophy</td>
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<td><strong>Prescription Type:</strong> Hypertrophy/Strength</td>
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<td><strong>F:</strong> 3-5 times/week, <strong>I:</strong> Body weight (60-90+ degrees of knee flexion), <strong>T:</strong> Isometric, <strong>V:</strong> 3-4 sets of 45-90 second isometric contractions</td>
<td></td>
<td><strong>F:</strong> 3-5 times/week, <strong>I:</strong> Body weight (60-90+ degrees of knee flexion) on involved limb, <strong>T:</strong> Isometric, <strong>V:</strong> 3-4 sets to volitional fatigue</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>T:</strong> 0-90+ degrees of knee flexion, <strong>P:</strong> Progression of knee flexion angle, positive shin angle or external resistance</td>
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<tr>
<td><strong>Month 3-4</strong></td>
<td><strong>Leg Press Machine (Single-Leg with Blood Flow Restriction)</strong></td>
<td><strong>Split-Squat (60-90+ Degrees Knee Flexion)</strong></td>
<td><strong>Knee Extension Machine (Single-Leg with Blood Flow Restriction)</strong></td>
</tr>
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<td></td>
<td><strong>Prescription Type:</strong> Hypertrophy/Strength</td>
<td></td>
<td><strong>Prescription Type:</strong> Hypertrophy/Strength</td>
</tr>
<tr>
<td></td>
<td><strong>F:</strong> 2-4 times/week, <strong>I:</strong> Body weight (60-90+ degrees of knee flexion) on involved limb, <strong>T:</strong> Isometric, <strong>V:</strong> 3-4 sets to volitional fatigue</td>
<td></td>
<td><strong>F:</strong> 2-4 times/week, <strong>I:</strong> Body weight (60-90+ degrees of knee flexion) on involved limb, <strong>T:</strong> Isometric, <strong>V:</strong> 3-4 sets to volitional fatigue</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td><strong>T:</strong> 0-90+ degrees of knee flexion, <strong>P:</strong> Progression of knee flexion angle, positive shin angle or external resistance</td>
</tr>
<tr>
<td>Postoperative Month</td>
<td>Single-Leg Progression</td>
<td>Split-Squat Progression</td>
<td>Open-Kinetic-Chain Progression</td>
</tr>
<tr>
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<tr>
<td><strong>Month 4-6</strong></td>
<td><strong>Leg Press</strong> (Single-Leg with Increasing Load)</td>
<td><strong>Split-Squat</strong> (Rearfoot-Elevated Position)</td>
<td><strong>Knee Extension Machine</strong> (Single-Leg with Increasing Load)</td>
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<td>Prescription Type: Hypertrophy/Strength</td>
<td>Prescription Type: Hypertrophy/Strength</td>
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</tr>
<tr>
<td>F: 2-4 times/week</td>
<td>F: 2-4 times/week</td>
<td>F: 2-4 times/week</td>
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<tr>
<td>I: 6-15 RM (65-85% 1-RM) on the involved limb</td>
<td>I: 6-15 RM (65-85% 1-RM) on the involved limb</td>
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<tr>
<td>T: Isotonic (concentric/eccentric phase)</td>
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<tr>
<td>T: 5-10 minutes each exposure</td>
<td>T: 5-10 minutes each exposure</td>
<td>T: 5-10 minutes each exposure</td>
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</tr>
<tr>
<td>V: 3-4 sets to volitional fatigue</td>
<td>V: 3-4 sets to volitional fatigue</td>
<td>V: 3-4 sets to volitional fatigue</td>
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<tr>
<td>2-5-minute rest periods between sets</td>
<td>2-5-minute rest periods between sets</td>
<td>2-5-minute rest periods between sets</td>
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</tr>
<tr>
<td>P: Progression of knee flexion angle, positive shin angle or external resistance</td>
<td>P: Progression of knee flexion angle, positive shin angle or external resistance</td>
<td>P: Progression of external resistance at the distal tibial</td>
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<tr>
<td><strong>Month 6+</strong></td>
<td><strong>Eccentric Leg Press</strong> (2-Legs Up Concentric / 1-Leg Down Eccentric)</td>
<td><strong>Split-Squat Jumps</strong> (Lunge or Rearfoot-Elevated Position)</td>
<td><strong>Eccentric Knee Extension Machine</strong> (2-Legs Up Concentric / 1-Leg Down Eccentric)</td>
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<td>Prescription Type: Power</td>
<td>Prescription Type: Hypertrophy/ Eccentric Strength</td>
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</tr>
<tr>
<td>F: 2-3 times/week</td>
<td>F: 2-4 times/week</td>
<td>F: 2-3 times/week</td>
<td></td>
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<tr>
<td>I: 1-5 RM (85-100% 1-RM) on the involved limb</td>
<td>I: Body weight to 40-60% 1-RM on the involved limb</td>
<td>I: 1-5 RM (85-100% 1-RM) on the involved limb</td>
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<tr>
<td>T: Eccentric resistance training</td>
<td>T: Isotonic (concentric/eccentric phase), emphasis on speed/effort during the concentric phase of the movement</td>
<td>T: Eccentric resistance training</td>
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</tr>
<tr>
<td>T: 5-10 minutes each exposure</td>
<td>T: 5-10 minutes each exposure</td>
<td>T: 5-10 minutes each exposure</td>
<td></td>
</tr>
<tr>
<td>V: 3-4 sets of 8-15 eccentric repetitions</td>
<td>V: 4-5 sets of 3-5 reps</td>
<td>V: 3-4 sets of 8-15 eccentric repetitions</td>
<td></td>
</tr>
<tr>
<td>2-5-minute rest periods between sets</td>
<td>2-5-minute rest period between sets</td>
<td>2-5-minute rest periods between sets</td>
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</tr>
<tr>
<td>P: Progression of knee flexion angle, positive shin angle or external resistance greater than a 1-RM (e.g., 120% 1-RM)</td>
<td>P: Progression of knee flexion angle, positive shin angle, contraction speed or external load</td>
<td>P: Progression of external resistance greater than a 1-RM (e.g., 110% 1-RM)</td>
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F, frequency; I, intensity; T, time; V, volume; P, progression; AROM, active range-of-motion; TKE, terminal knee extension; LOP, limb occlusion pressure, RM, repetition maximum, 1-RM, 1-repetition maximum
focus on force-transmission. Specifically, performing the prone knee flexion stretch will preferentially tension the superficial layer of the quadriceps tendon by maximally lengthening rectus femoris, compressing/shearing the deeper layers of the tendon\cite{95,97,98}; this unique type of tendon loading can be prescribed in addition to strength training to mobilize the graft harvest site and may help stimulate quadriceps tendon remodeling (Figure 2).

Months 2–4 after ACLR with the QT, the CKC quadriceps load-progression should include isometric or isotonic contractions with a light to moderate external resistance. Initially, body weight isometric exercise in low levels of knee flexion may best manage graft harvest site irritability\cite{94,99} (Figure 1A) (Table 2). As exercise tolerance improves, the quadriceps load-progression should be advanced by monitoring the graft harvest site for any increase in pain/irritability with exercise while gradually progressing external resistance or the level of knee flexion\cite{95} (Figure 1A-D-E). The rehabilitation specialist should not advance too many variables at once, as simultaneously increasing external resistance and the level of knee flexion can exponentially load the quadriceps tendon and may provoke graft harvest site pain\cite{94,95} (Figure 1C).

Graft-specific load-progressions for the P-QT may also exist, in which more specific targeting of the superficial layer of the quadriceps tendon/rectus femoris with OKC exercise may be indicated.\cite{98,100} The long-arc-quad exercise should be advanced from active range-of-motion during the early phase of rehabilitation,\cite{85} to OKC quadriceps resistance training on a knee extension machine (Table 2); the rehabilitation specialist may elect to perform OKC quadriceps resistance training with the hip positioned in lower levels of hip flexion to preferentially load rectus femoris (i.e., performing OKC quadriceps resistance training with the trunk positioned in supine).\cite{95,97,98} External resistance should be thoughtfully progressed, as performing OKC quadriceps resistance training between 0–45 degrees of knee flexion will increase patellofemoral compartment stress and preferentially strain the reconstructed ACL graft\cite{85,86,101} (Figure 3A), whereas performing OKC quadriceps resistance training in deeper levels of knee flexion will preferentially load the quadriceps tendon and may provoke irritability at the graft harvest site\cite{94,95} (Figure 3B).

**LATE PHASE (POSTOPERATIVE WEEKS 16+)

As the surgical limb develops the capacity to perform higher-load activities at slow contraction velocities, higher demand exercise progressions should be introduced. Patients participating in physically demanding activities, such as Level 1 sports, will benefit from exposure to plyometric and ballistic-type exercise progressions. The rehabilitation specialist should consider the quadriceps tendon a rate-limiting tissue for the introduction of plyometric exercise,\cite{23} as the QT harvest site must store and transfer energy during these progressions. Plyometric exercise should be initiated with knee-specific regimens that temper the demand for elastic energy-storage within the quadriceps tendon, such as running drills in triple-extension or frontal plane plyometric exercise\cite{94,102,103} (Figure 4).

As mentioned previously, specific consideration should be given for ballistic activities that require the quadriceps tendon to transfer load while in the combined position of hip extension and knee flexion, such as the wind-up phase of kicking or high-velocity running\cite{104,105} (Figure 2B); these activities combine high angular velocities and tendinous compressive/shear force by the selective-tensioning of the superficial layer of the quadriceps tendon running continuous with rectus femoris.\cite{95,97} Sagittal plane deceleration training will also preferentially load the quadriceps tendon. During deceleration, the combination of large external knee flexion moments, increasing knee flexion angles, and high-force eccentric quadriceps contractions can produce exponentially higher load-transmission within the quadriceps tendon (Figure 4); sagittal plane deceleration training must be thoughtfully progressed per exercise-tolerance and symptom-response at the graft harvest site.

**RETURN TO ACTIVITY CONSIDERATIONS

Regardless of the graft type used for ACLR, most individuals expect to restore knee joint stability and function to a level that supports the return to their pre-injury activity level.\cite{106} However, only 65% of individuals may return to their pre-injury level of sports participation,\cite{107} with knee re-injury rates between 20–30% within higher-risk cohorts.\cite{108–110} Equally troubling is the unclear association between return-to-activity testing batteries and the subsequent risk of knee re-injury within various cohorts,\cite{111–117} and although the restoration of limb function on objective performance tests appears to improve return-to-sport rates,\cite{118–120} the use of performance testing cut-points as strict, medically-required, return-to-activity criteria remains controversial.\cite{112,121–123} Recent literature has highlighted the importance of shared decision-making after ACLR,\cite{124,125} to which the use of a decision-making framework may improve the return-to-activity decision-making process,\cite{124,126–129}

To best inform shared decision-making, serial physical examinations and performance testing batteries should be completed throughout rehabilitation.\cite{130,131} Physical examinations should include the assessment of knee homeostasis (effusion and irritability), stability and range-of-motion.\cite{132} After ACLR with the QT, quadriceps strength testing should be a fundamental component of the performance testing battery, as quadriceps strength appears most affected by QT harvest.\cite{33,34,68} Quadriceps strength deficits are common 9–12 months after ACLR.\cite{34} Other components of a performance testing battery may include jump/hop testing and the assessment of movement quality; these tests should include both qualitative and quantitative measurements.\cite{132} Collectively, this information can be utilized throughout rehabilitation to confirm the effectiveness of exercise interventions, adjust the exercise prescription(s), and inform return-to-activity decision-making.\cite{133}

Of the various data synthesized for return-to-activity decision-making, some information may be more important than others. The timeframe between ACLR and return-to-activity has been observed to be a modifiable risk factor.

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### Table 3. Rehabilitation Overview

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Location</th>
<th>Description of Consideration(s)</th>
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<tr>
<td><strong>Early Phase Rehabilitation Considerations (Postoperative Weeks 0-8)</strong></td>
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</table>
| Graft Composition | Intra-Articular | B-QT  
- Partial graft osteointegration within first 4-6 weeks  
S-QT  
- Graft fibrovascular integration takes a minimum of 10-12 weeks  
- Accelerated rehabilitation approaches may be less appropriate when fixated with suspensory fixation (Table 2)  
F-QT  
- Consider risk of a range-of-motion complications with large graft diameter and robust biomechanical properties |
| OKC Quadriceps Resistance Training / Graft Fixation | Intra-Articular | OKC Exercise with Interference Screw Fixation (B-QT)  
- AROM: as tolerated  
- OKC quadriceps resistance exercise with distal tibial load:  
  - 45-90+ degrees weeks 3-4  
  - 0-45+ degrees weeks 4-6+  
OKC Exercise with Suspensory Fixation (S-QT)  
- AROM: as tolerated  
- OKC quadriceps resistance exercise with distal tibial load:  
  - 45-90+ degrees weeks 3-10  
  - 0-45+ degrees weeks 10-12+ |
| **Middle Phase Rehabilitation Considerations (Postoperative Weeks 8-16)** |  |  |
| Graft Composition | Extra-Articular | B-QT  
- Low risk of patellar fracture (1.4-8.8%)  
F-QT  
- Possibility of more persistent and global quadriceps inhibition  
- Differentiation of a postoperative knee effusion from a suprapatellar hematoma at graft harvest site |
| Graft Harvest Site | Extra-Articular |  |
| **Late Phase Rehabilitation Considerations (Postoperative Weeks 16+)** |  |  |
| Graft Composition | Extra-Articular | Ongoing Quadriceps Strengthening Program  
- Quadriceps strengthening program 2-3x/week (OKC + CKC)  
- Progressive resistance training, eccentric training, and power training  
Progression of Energy Storage Activities into Increasing Knee Flexion  
- Combination of hip extension and knee flexion preferentially tens the superficial layer of the quadriceps tendon (e.g., wind-up phase of kicking)  
- Avoid acute spikes in plyometric load into increasing levels of knee flexion  
- Thoughtful progression of high velocity running speed/intensity, distance and volume  
- Thoughtful progression of high-velocity kicking and sagittal plane deceleration training |
| Graft Harvest Site | Extra-Articular |  |

B-QT, quadriceps tendon autograft with patellar bone-block; S-QT, all soft-tissue quadriceps tendon autograft; F-QT, full-thickness quadriceps tendon autograft; OKC, open-kinetic-chain; AROM, active range-of-motion; P-QT, partial-thickness quadriceps tendon autograft; CKC, closed-kinetic-chain
**Figure 2. Selective tensioning of the superficial layer of the quadriceps tendon**

Selective tensioning of the superficial layer of the quadriceps tendon is achieved by maximally lengthening rectus femoris into the combined motion of hip extension and knee flexion; low-velocity stretching may be therapeutically prescribed to shear/mobilize the graft harvest site (A), whereas high-velocity activities should be thoughtfully progressed with ongoing monitoring of the graft harvest site for any increase in tissue irritability. Asterisk, quadriceps tendon autograft harvest site; white lines, depiction of joint angles; black dash-arrow, high-velocity eccentric lengthening of the quadriceps muscle during the wind-up phase of kicking.

for knee re-injury,\(^{111,134}\) with the suggestion that most individuals should wait a minimum of nine months before returning to unrestricted sports participation.\(^ {111,122,132}\) Risk calculator algorithms formulated to predict the risk of revision ACLR have been recently validated for clinical use\(^ {135,136}\); these algorithms are based upon data that is specific to the individual of interest, including age, body mass index, preoperative knee laxity, activity level and graft type.\(^ {135,136}\) The ACL-Return to Sport after Injury (ACL-RSI) is a validated psychometric scale, and should be used to assess an individual's psychological readiness for sports participation after ACLR.\(^ {132}\)

Comprehensive rehabilitation and return-to-sport programming can facilitate improved limb function on objective performance tests,\(^ {133,137}\) achieve higher return-to-sport rates and reduce the risk of knee re-injury.\(^ {133,138–141}\)

Comprehensive programming should include formal strength and conditioning sessions, as well as the integration of jumping/hopping, cutting and sport-specific load-

**Figure 3. Considerations for open-kinetic-chain quadriceps resistance training with distal tibial load**

Performing quadriceps resistance training between 0-45 degrees of knee flexion with distal tibial load will produce higher patellofemoral joint stress and increase strain on the reconstructed anterior cruciate ligament (A), whereas performing resisted knee extensions in deeper levels of knee flexion will preferentially load the quadriceps tendon relative to the patellar tendon. Red arc, 0-45 degrees of knee flexion; yellow arc, >45 degrees of knee flexion; Black asterisk, quadriceps tendon autograft harvest site.

**Figure 4. Sagittal deceleration task vs lateral plyometric task**

The resultant ground reaction force during a sagittal plane deceleration task (top sequence from left to right) places a large amount of load on the knee and quadriceps tendon, whereas a lateral plyometric task places more relative load proximally on the lateral hip and trunk (bottom sequence from left to right). Red arrows, resultant ground reaction force-vector; white lines, depiction of joint angels; asterisks, area of high load-demand during task.

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progressions. Late phase load-progressions should include a period of on-field rehabilitation with all relevant stakeholders (e.g., athlete, coach, guardian, and rehabilitation specialist) in agreement with the return-to-practice and competition progressions. On-field rehabilitation should follow the control-chaos continuum and facilitate graded exposure to sports participation. On-field rehabilitation should follow the control-chaos continuum and facilitate graded exposure to sports participation. 

Prior to commencing unrestricted activity, a final physical examination and performance testing battery should be completed with all relevant information clearly synthesized for analysis within the shared decision-making framework. If the individual is returning to an activity with a high risk of knee re-injury, such as Level 1 sports, secondary injury reduction strategies should be implemented regardless of performance testing status. Pre-activity neuromuscular warmups, such as the FIFA 11+, appear highly effective at mitigating known biomechanical risk factors for anterior cruciate ligament injury and can significantly reduce the overall injury incidence rate.

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CONFLICTS OF INTEREST
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Clinical Commentary/Current Concept Review

The Implementation of a Return-to-Play Protocol with Standardized Physical Therapy Referrals in a Collegiate Football Program: PT’s Role in Return-to-Play, A Clinical Commentary

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Sport-related concussions (SRCs) are multi-faceted injuries requiring coordinated care for return-to-play (RTP). Although the number of concussions in collegiate football is increasing annually, there is poor standardization among RTP protocols. Recent evidence suggests there is an increased risk of lower extremity injury, neuropsychiatric consequences, and re-injury after SRC, and risk factors for a prolonged recovery from SRC have also been identified. Evidence demonstrates a faster RTP and improved outcomes with early physical therapy intervention; however, this is not yet common practice in the treatment of acute SRC.

There is little guidance available on the development and implementation of a multidisciplinary RTP rehabilitation protocol for SRC that incorporates standardized physical therapy. By describing an evidence-based RTP protocol with standardized physical therapy management, and measures taken to implement this protocol, this clinical commentary aims to identify steps in treating SRC that can be used to improve recovery. The purpose of this commentary is to: a) survey the current state of standardization of RTP protocols in collegiate football; b) highlight the development and implementation of a RTP protocol with standardized physical therapy referral and management in an NCAA Division II collegiate football program; and c) describe results of a full-season pilot study, including time to evaluation, time to RTP, rate of re-injury or lower extremity injury, and the clinical significance of protocol implementation.

Level of Evidence
Level V

BACKGROUND AND INTRODUCTION

Sport-Related Concussion (SRC) has become a frequent topic of discussion in the sports medicine world. Collegiate football is often the focal point of this discussion due to the high relative risk of SRC. A recent epidemiologic study of SRCs in National Collegiate Athletic Association (NCAA) sports indicated that men’s football has the highest annual rate of SRCs and the highest annual increase in the number of SRCs compared to other collegiate sports,1 with 26.1% of players in a collegiate football program experiencing a concussion at some point in their careers.2 Moreover, nearly 10% of SRCs in collegiate football are recurrent injuries.1 Concussions affect multiple body systems and can physically, cognitively, and psychologically impact a student-athlete. After a concussion, athletes also may face a higher risk of lower extremity injury3 and potential long-term cognitive and neuropsychological consequences.4

To improve concussion management in collegiate athletics, the NCAA implemented a policy in 2010 that addressed the need for a concussion management plan for member institutions. That plan includes removal from play for medical examination of any athlete exhibiting concus-
sion-related symptoms, preclusion of return-to-play (RTP) for any athlete diagnosed with a concussion, and medical clearance to resume play following a concussion diagnosis.\(^5\) There was an increase in the number of diagnosed concussions in collegiate football following the implementation of this policy,\(^2\) highlighting the need for sensitive testing and quality rehabilitation protocols. The lack of sensitive measures for diagnosis and readiness to RTP can ultimately lead to premature RTP. Baugh et al. studied 730 collegiate football players and found that for every diagnosed concussion, there were 4.125 undiagnosed concussions in an athlete's career, on average.\(^6\) Furthermore, a five-year, retrospective study by Carson et al. found that 43.5% of SRCs returned to play too soon.\(^7\)

SRCs are challenging to manage due to the underlying pathophysiology. A rapid change in intracranial velocity results in axonal shearing and cerebral edema creating metabolic changes and reduced cerebral blood flow.\(^8\) Force directed to the head and neck area can also create cervical spine soft tissue, articular, and ligamentous damage,\(^9\) resulting in varying symptoms, recovery times, and clinical trajectories. Presentations can differ greatly amongst athletes, but deficits can include vestibular and ocular impairments, musculoskeletal and cervical impairments, impairments in sensory integration, deficits in motor control, as well as autonomic dysfunction and exertional intolerance.\(^10,11\)

SRCs are most commonly managed by team athletic trainers (ATCs) and team physicians (MDs).\(^12,13\) However, it has been demonstrated that physical therapy can effectively address impairments related to SRC.\(^10\) Authors have demonstrated that individuals post-concussion who received individualized physical therapy were 3.91 times more likely to be cleared to RTP after eight weeks,\(^10\) and athletes receiving individualized physical therapy within 10-days post-concussion are medically cleared for RTP significantly faster.\(^14\) Both cervical and vestibular rehabilitation are recommended by the 5th Consensus Statement of Concussion in Sport\(^15\) and pre-morbid risk factors and post-injury prognosticators identifying athletes that are at risk for a prolonged recovery have been established.\(^15,16\) Despite this, referral to physical therapy following SRC is frequently at the discretion of team ATCs and MDs as needed for complex vestibular and/or cervical issues or for athletes with persistent symptoms.\(^15\)

When considering return-to-learn (RTL), improved clarity is also advantageous. The 5th Consensus Statement of Concussion in Sport presents a recommended four-step return-to-school strategy if needed;\(^15\) however, outside of this recommendation, it provides no definitive criteria for academic accommodations or stepwise progression, the timing of stepwise progression, or multi-disciplinary involvement in addressing cognitive deficits. Although prolonged and complete cognitive rest has been shown to delay recovery,\(^17\) Carson et al. found that 44.7% of athletes with SRCs returned to full academic participation too soon, and findings from the Ivy League–Big Ten Epidemiology Study show that athletes who return to full academics too soon take longer to recover from SRC and that improved clarity in the timing of RTL is warranted.\(^7,18\) Authors have suggested that impairments in working memory and attentional control can also lead to impairments in lower extremity motor control.\(^19\) However, these domains can be improved with targeted interventions, including physical therapy.\(^19\)

Despite current efforts to better understand and manage SRCs, concussions remain one of the most complex injuries in sports-medicine, making it difficult to identify and implement best practices for a standardized RTP protocol. To develop a protocol that best serves the student-athlete, it is important to understand the landscape of RTP protocols as well as current, evidence-based concussion rehabilitation. Enhancing existing RTP protocols with recently available evidence can reduce premature RTP, improve rehabilitation effectiveness, and expedite recovery for athletes at risk for persistent symptoms.

With the changing landscape of RTP protocols and SRC management, the purpose of this clinical commentary is three-fold: to a) survey the current state of standardization of RTP protocols in collegiate football; b) highlight the development and implementation of a RTP protocol with standardized physical therapy referral and management in an NCAA Division II collegiate football program; and c) describe results of a full-season pilot study, including time to evaluation, time to RTP, rate of re-injury or lower extremity injury, and the clinical significance of protocol implementation. It is hoped that this commentary will aid in the strengthening of RTP protocols by demonstrating the benefit of increased and standardized physical therapy management in RTP. This study has been approved by the Mercer University Institutional Review Board.

**CURRENT STANDARDIZATION OF RETURN-TO-PLAY PROTOCOLS**

Along with the NCAA's updated policy regarding SRCs, position statements have been published by several professional organizations with recommendations for SRC management. The most recent Consensus Statement by the Concussion in Sport Group, 2017, presents an updated return-to-sport strategy consisting of a graduated six-step rehabilitation protocol.\(^15\) Recommendations for the recognition of a concussion, sideline evaluation and re-evaluation of a concussion, and removal from and reintroduction to play are also discussed.

The National Athletic Training Association (NATA) released a position statement in 2014 with notable recommendations including documentation of an athlete's concussion evaluation and progression through a RTP protocol, baseline pre-season examinations that include neurocognitive and balance measures for high-risk sports, diagnosis reached by clinical examination and assessment tools, and treatment of athletes on an individual basis.\(^12\) The NCAA has also presented a Concussion Safety Protocol Checklist and Concussion Safety Protocol Template to serve as a guide in the development and standardization of RTP protocols.\(^20\) The checklist recommends pre-season education presented to athletes, pre-season assessment of concussion.
history, symptom evaluation, cognitive evaluation, and balance evaluation. A six-step return-to-sport plan is also required.

In 2015, Kerr et al. performed a cross-sectional investigation of concussion-related protocols and pre-season assessments that involved all 1,113 NCAA member institutions via surveys sent to all head ATCs. Despite the recommendations for standardized concussion management, results demonstrated that the adherence to recommendations vary by policy and division. Most, but not all, institutions provided concussion education to athletes (95.4%) and had RTP policies (96.6%), while fewer had RTL policies (63.3%). Only 83.2% of institutions utilized pre-season neuropsychological testing and only 56.6% incorporated balance assessments. The adherence to NATA recommendations also differed by division, with 55.2% of Division I programs complying with baseline measure recommendations compared to 38.2% and 36.1% of Division II and Division III institutions, respectively.

In 2017, Buckley et al. evaluated the concussion management plans of all 65 Power Five NCAA institutions for compliance with the NCAA’s 2010 concussion policy. The overall compliance was 94.3% but varied greatly in detail and length, with one institution only complying with 59.6% of components. The lowest domain for institutional compliance was return-to-learn, with only 86.4% of components addressed. Although the overall compliance rate was high, there continues to be room for improvement.

Both the consensus statement by the 5th CISM and the NCAA’s Concussion Safety Protocol Checklist recommend referral for multi-discipline management but not until symptoms become "persistent," despite evidence that individualized and early onset of physical therapy intervention reduces recovery time and risk for persistent symptoms. Furthermore, to the authors' knowledge, there is no literature describing the standardization of concussion rehabilitation or referral to physical therapy within collegiate football.

The variability in RTP policies between schools and divisions can be due to multiple factors, including but not limited to differing education levels, institutional support or financial limitations, or access to medical professionals, including physical therapists specializing in SRC management. However, universities and health care providers need to continue to adapt current policies with current evidence that better protect and serve student-athletes.

RETURN-TO-PLAY PROTOCOL

The implemented RTP protocol, described below, involving multi-disciplinary care from time of injury to full clearance, was developed utilizing recommendations from the 5th CISM consensus statement and NCAA Safety Protocol Checklist, and meets compliance with NCAA legislation. The protocol includes objective baseline neuromotor and neurocognitive testing, standardized sideline assessments, and a six-step RTP progression incorporating individualized physical therapy treatment. Evidence-based risk factors for prognostication were utilized at the time of injury to standardize referral to physical therapy.

It is important to note that the team athletic trainers, team physician, physical therapists, and speech-language pathologist were contracted from a local hospital system and were not university employees. Team ATCs were located within the university’s athletic facility; however, a sports-medicine fellowship-trained physician and physical therapist specialized in concussion management were based in satellite clinics off campus. Educational inservices were provided among disciplines to ensure the proper use of assessments and outcome measures for standardization of care.

BASELINE ASSESSMENTS

All athletes participated in pre-season physical examinations before being cleared to participate. Baseline neurocognitive performance and baseline symptoms were assessed via the Immediate Post-Concussion and Cognitive Testing (ImpACT) battery. It has been demonstrated that the ImpACT test battery has a low to moderate test-retest reliability with up to a 26% rate of purposeful underperformance by athletes; therefore, a multimodal objective assessment is advantageous to assess readiness to RTP. Evidence demonstrates that individuals who are post-concussion have impaired postural stability and sensory integration compared to non-concussed individuals. Therefore, objective baseline assessments of neuromotor function were performed.

A four-condition Clinical Test of Integration in Balance (CTSIB) was performed utilizing a dynamic force plate to gather objective data on baseline postural stability and sensory integration. It has been shown that athletes with a history of concussion can demonstrate clinical deficits in balance long after the initial injury; therefore, baseline norms were utilized as reference during RTP. Standard deviations for sway values on all four conditions in collegiate athletes were gathered in a study by Moran et al. and were utilized as a second comparison during recovery post-injury. The mBESS was not recorded due to concerns over ceiling effects. Education regarding symptoms and risks of SRC and the purpose of RTP protocol was also provided during pre-season physicals.

SIDELINE ASSESSMENT OF INJURY

To increase the sensitivity of clinical diagnosis, ATCs were educated on standardized sideline assessments of vestibular function, including the Vestibular Ocular Motor Screening (VOMS) and modified Concussion Balance Test (mCOBALT), to be performed in conjunction with the Sport Concussion Assessment Tool (SCAT-5). Sideline evaluations also incorporated the assessment of evidence-based negative prognosticators and/or risk factors for a prolonged recovery from SRC. These assessments served as a framework for referral to skilled PT, as athletes identified as at-risk for a prolonged recovery by the ATC and MD were referred to skilled PT.
The VOMS briefly screens vestibulo-ocular and oculomotor function and sensitivity. The VOMS can be used to aid in diagnosis of concussion with any item scored ≥ 2 in sensitivity increasing diagnostic accuracy of a concussion by 46%.10 The addition of the VOMS has been demonstrated to significantly increase the overall sensitivity and diagnostic capability of the SCAT-5.28 To further assess balance if needed, ATCs were educated on the use of the mCOBALT, which is a four-minute exam derived from the CTSB and is more sensitive in identifying concussion-related neuromotor impairment than the mBESS due to increased vestibular demand.29 On average, only 55% of concussed athletes can complete the exam due to symptom provocation or loss of balance in comparison to 100% of non-concussed athletes.29

A decision tree was implemented for ATC use during sideline evaluation to identify athletes who are at risk of prolonged recovery from SRC according to evidence-based negative prognosticators post-concussion and/or risk factors (Figure 1). Pre-morbid risk factors include a history of previous concussion, migraines or familial history of migraines, history of anxiety and/or depression, Attention Deficit Disorder (ADD) or Attention Deficit/Hyperactivity Disorder (ADHD), female gender, and age less than 18 years.30–32 Athletes with any risk factors have a 55-69% increased risk of recovery greater than 21 days.30

Post-injury negative prognosticators include on-field dizziness, acute vestibulo-ocular abnormalities, post-traumatic migraine, or high initial symptom burden.30,33,34 Those with reports of on-field dizziness have a six-fold increase in risk for a recovery >21 days.34 The Vestibular Ocular Motor Screen can also be utilized to identify the risk of prolonged recovery in collegiate athletes.35 An abnormal score of ≥2 on smooth pursuits, horizontal and vertical saccades, or near-point convergence has been associated with a longer time to RTP.35

PHYSICIAN EVALUATION

To reduce the time from sideline assessment to clinical evaluation by the team physician and physical therapist, a communication portal was created between the ATC, MD, PT, and physical therapy office staff. Once a concussion was suspected, the ATC notified the MD to begin clinical management. It was also communicated by the ATC and MD if an athlete was considered a candidate for skilled PT to coordinate care with the physical therapist. If the MD was able to examine the athlete at the time of injury and deemed PT appropriate due to the risk of a protracted recovery, a referral to PT was placed to aid in the onset of early PT intervention.

The goal was to allow for MD and PT clinical evaluations to be performed within 48 and 96 hours of acute injury. Education on the pathology of concussion, symptoms, recovery trajectory, and RTP protocol was provided during evaluation. Each athlete was educated on limiting cognitive strain, visual strain including phone and computer use, and exertion during the first 48 to 72 hours post-injury. Education on RTL guidelines was also provided during MD evaluation, as described in detail below.

PHYSICAL THERAPY EVALUATION AND MANAGEMENT

Physical therapy evaluation assessed constructs in agreement with the American Physical Therapy Association’s clinical practice guideline on concussion management and was directed by each athlete’s presentation.10 Subjective evaluation investigated current symptoms, level of sensi-
tivity, individual functional goals, and the Post-Concussion Symptom Scale. Objective assessments for vestibular and vestibulo-ocular function, cervical spine integrity, exer-
tional tolerance, and neuromotor function were performed, guided by an athlete’s symptom sensitivity.

A Vestibular Ocular Motor Screen was performed to assess for vestibulo-ocular dysfunction. The VOMS incorporates five vestibulo-ocular and oculomotor domains: smooth pursuit, horizontal and vertical saccades, near-point convergence distance, horizontal vestibular ocular reflex (VOR), and visual motion sensitivity (VMS) and has an excellent internal consistency (α = .92), This was not compared to sideline performance of the VOMS, which was used to aid in diagnosis, but utilized to identify vestibulo-ocular impairments and sensitivities for guided treatment.

A Motion Sensitivity Quotient (MSQ) was also performed if motion sensitivity was subjectively reported or suspected. The MSQ was designed to identify and measure motion-provoked dizziness via 16 rapid body or head movements and was used clinically to develop an individualized exercise program for motion habitation. Both vestibulo-ocular and motion sensitivities were incorporated into later stages of rehabilitation via sport-related movements and drills. If room-spinning vertigo was reported, a screen for benign positional vertigo (BPV), including the Dix-Hallpike Test and Supine Roll Test, was performed for posterior/anterior and horizontal canal BPV, respectively.

If motion sensitivity or gaze instability was reported, a vestibular head impulse test (HIT) was performed to screen for peripheral vestibular hypofunction. A HIT directly assesses the vestibular-ocular response from the peripheral vestibular system as the clinician rapidly and unpredictably turns the athlete’s head during visual fixation to assess instantaneous corrective eye movements. With vestibular hypofunction, the eyes move with the head during an unexpected head turn and must make a corrective movement to re-fix on the target, indicating impaired vestibulo-ocular response gain.

Cervical spine range of motion, accessory mobility, and soft tissue palpation were examined along with assessments for potential cervicogenic headache, cervicogenic dizziness, cervico-ocular dysfunction, and/or motor control impairments. The Cervical Flexion-Rotation test investigates cervicogenic headache and dizziness related to the first and second cervical facet joints by maximally flexing and rotating the upper cervical spine. Provocation of headache or dizziness with upper cervical approximation is considered positive (Sn: 0.91, Sp: 0.90). Cervico-ocular dysfunction was assessed via the Smooth-Pursuit Neck Torsion Test, which compares the oculomotor performance and sensitivity of smooth pursuits in neutral and in 45 degrees of rotation. Increased sensitivity and the presence of nystagmus with cervical rotation can indicate upper cervical-related oculomotor dysfunction (Sn: 0.90, Sp: 0.91). Cervical joint position error was investigated if impairments in soft tissue mobility, cervical accessory mobility, or motor control were demonstrated. Cervical joint position error was assessed via the cervical joint relocation test, which utilizes a cervical laser harness to identify the degree of position error and cervical sensorimotor disturbances.

A post-injury objective CTSIB was performed for comparison to baseline data of balance and sensory integration, with symptom provocation also recorded. An mCOBALT test was not performed at the time of clinical evaluation as this was utilized as a part of the sideline examination to aid in diagnostic sensitivity. An mCOBALT was performed, however, prior to discharge to ensure no neuromotor impairment or vestibular sensitivities arose with more sensitive vestibular demands on balance.

To assess for autonomic dysfunction and/or exertional intolerance, a Buffalo Concussion Exercise Treadmill Test (BCTT) was performed. The BCTT gradually increases the intensity of exercise via treadmill incline while vitals and symptoms are assessed every one to two minutes. The test is discontinued if the athlete reaches voluntary exhaustion or if post-concussion symptoms are exacerbated. Heart rate was recorded at the onset or exacerbation of symptoms, which is considered the athlete’s heart rate threshold (HRT). If motion sensitivity was identified during vestibular examination, a modified Buffalo Concussion Bike Test (BCBT) was performed on an upright exercise bike to increase test specificity by accounting for potential increases in dizziness from a vertical translation during ambulation.

An individualized home exercise program was prescribed including interventions for cervical spine soft tissue mobility, cervical motor control, and vestibular habitation and/or adaptation. Graded aerobic exercise beginning less than 10 days post-injury has been associated with a faster RTP; therefore, daily sub-symptom aerobic cardiovascular exercise was prescribed utilizing the established HRT. Both the ATC and MD were informed of an athlete’s impairments, exercise program, and estimated prognosis for recovery.

Athletes continued individualized skilled physical therapy through stage three of the stepwise progression. Frequency was determined by impairments and severity. Interventions could include exercises for cervical spine motor control and proprioception, vestibular adaptation and/or habitation, exertional tolerance, and cervical vestibular ocular integration. Interventions also incorporated dual motor and cognitive task practice throughout all stages. All exercises incorporating vestibular or vestibulo-ocular tasks were performed at an intensity that provoked light to moderate dizziness (4-6 out of 10), or below migraine symp-
tom provocation. Once moderate dizziness was achieved, the athlete was instructed to rest until symptoms returned to baseline to promote vestibular habitation. Athletes continued to receive updated exercise programs reflecting their current RTP stage to be performed individually and supervised by ATCs.

**STEPWISE RETURN-TO-PLAY**

All athletes progressed through a six-step protocol as recommended from the 5th Concussion in Sport Group (CISG) meeting (Table 1), supervised by the ATC and PT under direction of the team MD. Stage zero began at the time of injury and included rest for the first 24-48 hours. Athletes then progressed to stage one which included vestibular and
Table 1. Stepwise Return-to-Play Protocol

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Activity</th>
<th>Goal for advancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Rest</td>
<td>Rest from non-ADL related physical exertion and cognitive strain for</td>
<td>• 48 hours post-injury</td>
</tr>
<tr>
<td></td>
<td></td>
<td>first 48 hours</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Graded Exercise</td>
<td>Symptom-dependent* graded aerobic and body weight exercise and</td>
<td>• Performance of 15 minutes of aerobic cardiovascular exercise at 70% heart rate max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vestibular and/or cervical interventions</td>
<td>without symptom provocation</td>
</tr>
<tr>
<td>2</td>
<td>Sport Related Exercise</td>
<td>Dynamic body weight exercise with increased vestibular†, vestibulo-ocular ‡, and/or cervical proprioceptive§ demand</td>
<td>• Completion of sport-related, body weight exercise workout without symptom provocation</td>
</tr>
<tr>
<td>3</td>
<td>Sport Related Drills</td>
<td>Introduction of weighted exercise focusing on sport-specific movements and explosion; performance of position-specific drills†† with increased vestibular, vestibulo-ocular, and cervical proprioceptive demand with cognitive and motor dual task practice**</td>
<td>• No symptoms at rest or with completion of readiness assessment or sport-related drills†† ** Lower extremity kinematics within normal limits with sport-related movement and cognitive dual task*** • ImPACT, CTSIB, mCOBALT within normal limits • Fully returned-to-learn without headache, cognitive impairments, or cognitive fatigue</td>
</tr>
<tr>
<td>4</td>
<td>Return to training</td>
<td>Full practice participant</td>
<td>• No symptoms at rest, with full practice participation, or within 24 hours of practice participation</td>
</tr>
<tr>
<td>5</td>
<td>Return to play</td>
<td>Full return to athletic competition</td>
<td></td>
</tr>
</tbody>
</table>

* Aerobic exercise should not exacerbate symptoms and is progressed daily as tolerated by symptoms
† Increased vertical and horizontal body movement and/or head movements, performed at an intensity below onset of moderate dizziness (4/10 to 6/10) to promote habituation
‡ Performance of ocular smooth pursuits, saccades, vestibulo-ocular gaze stability, convergence activities, and vestibulo-ocular cancellation
§ Increased cervical rotation and/or flexion and extension to one or both sides depending on involved cervical segments
** Sport-related tasks performed with memory retrieval, multiple/alternating motor tasks, or tasks dependent upon cues with time constraints
†† Dependent upon position, i.e. three-point stance and rush, pass/run block, hackepad, route running, drop back and scramble, side shuffle – performed with increased body movement, vestibulo-ocular tasks, cervical range of motion dependent upon individual sensitivities
*** Readiness assessment includes performance of 10 minutes moderate aerobic cardiovascular exercise, 10 minutes high intensity anaerobic cardiovascular exercise, 10-15 minutes sport-related body weight and weighted exercise, and 15 minutes sport/position-related drills with cognitive dual task
ImPACT: Immediate Post-Concussion Assessment and Cognitive Testing
CTSIB: Clinical Test of Sensory Integration in Balance
mCOBALT: Modified Concussion Balance Test

Cervical exercises provided by a physical therapist and sub-symptom aerobic conditioning guided by HRT identified via the BCTT or BCBT, if exertional intolerance and HRT were found.10 During each physical therapy session, athletes performed supervised aerobic cardiovascular exercise utilizing a treadmill or stationary bike and gradually increased their HR until either a new HRT was established or 70% HR max was achieved. Athletes could then progress to sport-related exercise (Stage 2 of RTP) with achievement of 70% HR max without symptom provocation and no symptoms at rest.

Stage 2 added sport-related body weight exercise, dynamic movement, and running drills supervised by the PT or ATC. Once athletes were able to perform sport-related exercise at moderate intensity (HR 70-80% HR max) without symptom provocation, they progressed to Stage 3, which incorporated non-contact sport-related drills, resistance training, and increased anaerobic demands. Both sport-related exercise and non-contact sport-related drills emphasized position-specific movements and vestibular, vestibulo-ocular, and cervical sensitivities specific to the athlete. A focal point of physical therapy intervention was the incorporation of dual motor and/or cognitive tasks throughout RTP progression.

Dual task is considered the performance of simultaneous motor or cognitive tasks.45 During open sports, such as football, athletes must regulate both internal processes (e.g., joint position sense, vestibular/ocular function) and respond to external cues (e.g., the ball, opponents, teammates) in order to modify movement and perform the in-
tended motor task such as running, cutting, blocking, catching, or tackling.\textsuperscript{19} The execution of these dual tasks occurs in time-constrained environments necessitating increased processing speed, reaction time, and working memory, all of which may be impaired post-concussion and can remained impaired after clearance to RTP.\textsuperscript{44,45} Impairments in these cognitive domains post-concussion have been correlated to abnormal LE kinematics when given a dual motor/cognitive task.\textsuperscript{44–46}

During physical therapy sessions, athletes were tasked to perform sport-related exercise or drills with simultaneous performance of vestibular or vestibulo-ocular tasks. These tasks also incorporated attentional control or working memory with time-constraints for processing speed. Examples are demonstrated in supplemental Videos 1 and 2.

Prior to progressing to stage four, athletes must have demonstrated CTISB sway data within one standard deviation of baseline and no symptoms or errors with performance of the mCOBALT to ensure neuromotor function within normal limits. Athletes must also have completed a readiness assessment performed by a physical therapist including high intensity aerobic and anaerobic exertion, sport-related exercise, and sport-related drills with dual motor and cognitive tasks (Table 1). Athletic training staff then progressed athletes to full-contact practice and full RTP as appropriate. Prior to participating in contact practice or full play, athletes must have demonstrated ImPACT testing results within normal limits, have fully returned to learn, and have received MD clearance.

RETURN-TO-LEARN

Although the focus of this commentary is on the introduction of standardized PT in RTP, a brief discussion of RTL is also important due to the lack of congruency amongst RTL protocols. To aid in consistency with RTL in this protocol, all athletes who demonstrated risk for a prolonged recovery were placed on a four-step RTL progression by the team MD. The stepwise progression was based upon the graduated RTL strategy recommended by the CISG\textsuperscript{13} and included: 1) performance of sub-symptom daily activities, 2) performance of school and other cognitive activities as guided by symptoms and beginning 48-72 hours post injury, 3) return to school part-time as advised by the MD, and 4) return to school full-time as advised by the MD or when the athlete can tolerate a modified schedule without symptom exacerbation, whichever occurred first. RTL progression was then communicated to the ATC, school academic counselor, and PT.

If appropriate, athletes returned to school part-time at 72 hours post-injury, as it has been suggested that strict rest longer than three days can protract recovery.\textsuperscript{17} Part-time participation could include partial attendance or shortened class periods, use of paper assignments to reduce visual strain, increased time for test taking, or increased breaks for symptom pacing, up to stage 4 of RTL. Athletes could not graduate from the stepwise progression until fully caught up on coursework and exams.

### Table 2. Results

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Mean/Median (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury to MD Evaluation</td>
<td>1.69</td>
</tr>
<tr>
<td>Injury to PT Evaluation</td>
<td>4.07</td>
</tr>
<tr>
<td>Time to RTP from PT Evaluation</td>
<td>12.93</td>
</tr>
<tr>
<td>Total time to RTP</td>
<td>17/15.5</td>
</tr>
<tr>
<td>Number of PT Visits</td>
<td>4.54</td>
</tr>
</tbody>
</table>

A referral for Speech-Language Pathology (SLP) was recommended if primary symptoms and/or impairments were consistent with the cognitive/fatigue clinical profile as described by Kontos et al.,\textsuperscript{47} if cognitive strain provoked post-traumatic migraine symptoms, or other cognitive impairments persisted past 10-14 days. Although SLPS are uncommon in traditional concussion management team, speech-language pathology is the second most common referral destination from a specialized concussion clinic, behind physical therapy.\textsuperscript{48}

In the context of concussion management, an SLP examines cognitive processing skills, divided attention, and working memory and provides strategies and skills to aid in active cognitive recovery.\textsuperscript{49} A communication portal was created including athletic trainers, team physician, and the university academic coordinator in which the SLP would provide insight into cognitive strategies to better individualize the RTL plan. Furthermore, the SLP would communicate to the physical therapist the cognitive domains in which an athlete had deficits, e.g., working memory, divided attention, in order for the PT to incorporate these demands into dual-task interventions.

RESULTS

A pilot study cohort for this approach consisted of 13 athletes who entered the concussion protocol, were identified to be at risk for a prolonged recovery by the team ATCs and MD, and were referred to skilled physical therapy. Results of time to MD evaluation, physical therapy evaluation, time to RTP after PT evaluation, and total time to RTP is demonstrated in Table 2. No athlete reported symptom exacerbation following clearance for RTP or full academic participation. Upon completion of the season, data was collected on the rate of re-injury following full RTP with no non-contact lower extremity injuries and one subsequent concussion occurring in the pilot cohort. It is worthwhile to note that there were also no subsequent concussions or LE injuries in any athlete in the cohort in the following football season.

DISCUSSION AND CLINICAL SIGNIFICANCE

The focus of this commentary is to describe the development and potential benefit of standardized physical therapy in a RTP protocol. It is hoped that the incorporation of sensitive sideline measures and evidence-based prognosti-
cation into sideline assessment aided in initiating early-onset individualized PT and improved outcomes. It has been demonstrated that athletes who receive clinical evaluation prior to eight days post injury have a decreased RTP time, with all PT evaluations occurring before this cut-off. The introduction of more sensitive diagnostic tools may have also positively affected outcomes by mitigating misdiagnosis, as athletes who suffer a concussion but continue to play are 2.2 times more likely to have a prolonged recovery.

More notably, all athletes in the pilot group initiated sub-symptom aerobic cardiovascular exercise prior to 10 days post-injury, began vestibular rehabilitation prior to 10 days post-injury, and received individualized vestibular and cervical rehabilitation and sport-related dual-task practice. Prior to discharge, neuromotor performance was assessed and compared to baseline CTSIB data, and athletes completed a PT-supervised readiness-to-return assessment to ensure adequate vestibular function, sensory integration and motor planning, and exertional tolerance. As mentioned above, no athlete had symptom exacerbation after full academic clearance or RTP.

Prior to the implementation of the protocol described, no records were kept of athletes’ concussion histories or RTP data by the university’s athletic department or athletic training staff; therefore, it is difficult to assess the improvements in RTP time or re-injury rate compared to previous seasons. However, there are several studies previously reported on concussion recovery in collegiate athletes. A 2021 study by Putukian et al. that included 1,152 collegiate athletes found the average time to full RTP was 20.21 days. The United States Air Force Academy also analyzed the recovery of 104 male division 1 collegiate athletes, finding a mean time to full RTP of 20.47 days and an increase in time to RTP for those with the pre-existing risk factor of a previous concussion ($1 = 35.9$ days, $2 = 48.4$ days). From 2015-2020, a large prospective cohort study was conducted analyzing concussion recovery data from 20 Ivy league and Big Ten Conference institutions. With data collected from 1,715 student-athletes, the median time to RTP was 14 days. The largest study conducted by the NCAA included data from 1,751 athletes across 22 academic institutions and reported that the median time to RTP was 12.8 days. All studies did report that a history of previous concussions was a risk for a longer recovery. However, no study reported data regarding athletes specifically referred to physical therapy. The variability of average time to RTP reported throughout the literature is noteworthy. However, despite all athletes in the cohort demonstrating risk for a prolonged recovery > 21 days and seven subjects having a history of one or more previous concussions, the average time of 17 days and median time of 15.5 days to RTP is comparable to larger studies.

Although the authors were unable to compare re-injury risk to previous seasons, it has been established that the risk of sustaining a subsequent concussion is significant, with an odds ratio of 5.73. Athletes may also be more likely to sustain a LE injury post-concussion, as Lynall et al. found that athletes are 1.97 times more likely to sustain an acute lower extremity injury within one-year post-concussion. As stated previously, there were no non-contact lower extremity injuries in this cohort. One athlete did sustain an ankle injury via another player falling onto the planted lower extremity. Due to the nature of the injury, it is difficult to assess if impaired motor control or motor planning increased the risk of this particular injury. One athlete sustained a second concussion later in the season; however, no athlete in the cohort sustained a subsequent concussion or LE injury in the following season, which is notable considering the increased risk of injury.

One athlete was referred to speech-language pathology as the primary symptoms/impairments were of the cognitive/fatigue clinical profile and the athlete demonstrated migraines with partial-school work that persisted longer than 14 days. However, no athlete reported symptom exacerbation with full academic participation.

There are several limitations to this pilot study. Firstly, there was no data collected regarding return-to-play, return-to-learn, or rate of post-concussion lower extremity injury prior to the implementation of this protocol, so a direct comparison of pre-implementation and post-implementation statistics is not possible. It is also important to note that three athletes did not return to athletic participation due to their decisions to discontinue play or withdraw from play with the intention to transfer to another university. These athletes did participate in skilled physical therapy and completed RTL guidelines, but their RTP data was not included in the study as they did not return to athletic participation. As mentioned above, there was one athlete who sustained a subsequent concussion. This injury occurred during the last week of the season; therefore, the data from the second injury was also not included in the data analysis, as the individual was playing in his final season and not attempting to return to play. These exclusions may have affected the results.

The authors also understand that the cohort involved in the study is very small and hesitate to make major interpretations from the data obtained. However, the authors believe that the results from the first year of protocol implementation and the discussion in this commentary have clinical relevance for collegiate athletic programs nationwide. This study continues to collect data on time to RTP and rate of re-injury with standardized referrals to skilled PT. Additional, larger, and multi-center studies are still needed to further examine the outcomes of standardized physical therapy in RTP protocols at the collegiate level.

CONCLUSION

The rate of sport-related concussions in collegiate football continues to increase and emerging data demonstrate that there are neurocognitive and neuromotor impairments that can persist past RTP. Professional organizations including the NATA, the NCAA, and the CISG have developed recent policies and recommendations to aid in SRC management; however, there continues to be a lack of continuity between policies amongst collegiate football programs and divisions of competition. Physical therapy management has been proven efficacious in reducing prolonged impairment post-
concussion and increasing time to RTP, but the inclusion of physical therapy in RTP protocols is not yet common practice.

This commentary presents a RTP protocol that incorporates standardized physical therapy referral and management. Despite all athletes in the associated pilot study cohort having risk factors for prolonged recovery, the results of this protocol as measured in time to RTP are comparable to larger studies. It is also notable that there was only one subsequent concussion and zero non-contact LE injuries in the cohort after two seasons of play. The authors hesitate to make major interpretations from this study due to the small sample size; however, this commentary demonstrates that the incorporation of standardized PT in RTP is feasible and may be efficacious for athletes at risk for a protracted recovery following SRC.

CONFLICT OF INTEREST
All authors disclose no conflict of interests.

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REFERENCES


SUPPLEMENTARY MATERIALS

**Video 1**

**Video 2**
Original Research

Ecological and Specific Evidence-Based Safe Return To Play After Anterior Cruciate Ligament Reconstruction In Soccer Players: A New International Paradigm

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Keywords: anterior cruciate ligament reconstruction, return to play, soccer specific, ecological approach, battery test

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Existing return to play (RTP) assessments have not demonstrated the ability to decrease risk of subsequent anterior cruciate ligament (ACL) injury after reconstruction (ACLR). RTP criteria are standardized and do not simulate the physical and cognitive activity required by the practice of sport. Most RTP criteria do not include an ecological approach. There are scientific algorithms as the "5 factor maximum model" that can identify risk profiles and help reduce the risk of a second anterior cruciate ligament injury. Nevertheless, these algorithms remain too standardized and do not include the situations experienced in games by soccer players. This is why it is important to integrate ecological situations specific to the environment of soccer players in order to evaluate players under conditions closest to their sporting activity, especially with high cognitive load. One should identify high risk players under two conditions: Clinical analyses commonly include assessments such as isokinetic testing, functional tests (hop tests, vertical force-velocity, profile), running, clinical assessments (range of motion and graft laxity), proprioception and balance (Star Excursion Balance Test modified, Y-Balance, stabilometry) and psychological parameters (kinesophobia, quality of life and fear of re-injury). Field testing usually includes game simulation, evaluation under dual-task conditions, fatigue and workload analysis, deceleration, timed-agility-test and horizontal force-velocity profiles. Although it seems important to evaluate strength, psychological variables and aerobic and anaerobic capacities, evaluation of neuromotor control in standard and ecological situations may be helpful for reducing the risk of injury after ACLR. This proposal for RTP testing after ACLR is supported by the scientific literature and attempts to approximate the physical and cognitive loads during a soccer match. Future scientific investigation will be required to demonstrate the validity of this approach.

Level of Evidence

5

INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most controversial injuries in the world of sports. For example, ACL injury represents only 14% of injuries in soccer, but causes physiological and psychological modifications that can compromise the progress and career of soccer players. Forsythe et al. showed that only 71% of injured players return to their previous level within one year after the injury and only 81% return within three years. If the return to the previous level is difficult after an ACL reconstruction (ACLR), it also appears that return to play (RTP), and at high level, can be hampered by a significant number of re-injury, as shown by Della Villa et al. The safest possible RTP is a major sporting and economic challenge after ACLR.

Hence, implementation of functional assessments is important in the return to sport and RTP decisions for soccer players. If the isokinetic assessment, the hop tests and the psychological assessment seem to be gold standards it is...
important to note that these assessments are neither scientifically validated nor capable of predicting the risk of recurrence.\textsuperscript{5,6} Others authors have highlighted the lack of specificity and ecological situations in soccer player assessment as close as possible to their activity.\textsuperscript{7–10}

It is important to develop ecological tests based on the specific skills of the soccer player and on solid scientific algorithms. Thus, the proposed test sequence is based on the "5 factors maximum model" developed by Hewett et al. aimed at prediction of ACL injury risk\textsuperscript{11} but also on ecological situations that result from the "11 to perf" assessment developed by Clairefontaine at the FIFA Medical Center. The 5-factor maximum model is based on anthropometric, strength and coordination, biomechanics, proprioception and balance, and psychological characteristics.\textsuperscript{11,12} In addition, it is important to develop quantitative and qualitative tests with reliable and recommended evaluation tools (robotic laximetry, force platforms, etc.). The use of a scientific algorithm predictive of ACL injury that complements the existing tests, while approximating ecological situations, is a clinically relevant means of being able to make a safe decision in the RTP after ACLR in soccer player. Thus, it seems important to us to divide the suggested assessment into two stages (or 2 phases): Clinical using results from standardized tests, and field using results from an ecological situation specific to the soccer player’s environment (\textit{Table 1}).

\textbf{THE FIRST STEP: CLINICAL ASSESSMENTS}

Before performing a sequence of tests allowing the return to the field, it is necessary to ensure the motor abilities of the patient such as walking without limping, or the return to running.

\textbf{RUNNING}

Running activity during rehabilitation of a patient after ACLR is unfortunately usually not sufficiently addressed.\textsuperscript{13} Often, running activity is a generic term that includes running in water, in-place running, running on a treadmill (with or without altered gravity), or educational running exercises, jogging, stadium running, trail running... Hence, rehabilitative management should focus on gradually increasing running demands through a continuum of exercises and activities in preparation for sprinting and changing directions (cutting/pivoting).

After ACLR, the return to running can be initiated very early (two months postoperatively) as previously proposed (see Rambaud et al. 2018) and but only with normal clinical criteria (no pain, full range of motion, operationalized knee flexion and extension strength).\textsuperscript{14}

However, in current clinical practice, it is commonly during the fourth postoperative month that most patients are allowed to resume running (from three months postoperatively).\textsuperscript{15,16} This time frame is proposed to consider the biological processes of integration of the graft into the bone tunnels and the general healing of the knee joint.

Even if running induces little stress on the ACL (and by extension, the same for the graft), it remains a stressful activity for the femorotibial and patellofemoral joints, which can result in altered loading and pain, which is seen as a limp (running with low knee flexion, or with a dynamic valgus).\textsuperscript{16} A clinical assessment and a test battery seems to be essential to consider the start of running and a running program is initiated according to the patient’s abilities found during these evaluations (e.g. Delaware Interval Running Protocol).\textsuperscript{17} To ensure optimal loading program, the patient’s voice and her/his opinion will be essential. The use of soreness rules is important to avoid major errors in running training.\textsuperscript{18}

Thus, a dialogue must be established, and the program adjusted according to the different elements with which the patient presents (pain, difficulties, fears). Running progression protocol will be continued until interval running protocol, running at high speed, or even sprinting to prepare for side cutting and pivoting activities and return to sport continuum.\textsuperscript{19}

At the time of return to play, a running assessment on a treadmill is useful to evaluate if the running pattern is correct and symmetric. Indeed, even if lower limb dominance can play on asymmetry, it remains rather weak, particularly on lower limb stiffness (between 0 and 3%). The use of an optoelectrical barrier such as the OptoGait (Microgait, Tours, France) can provide an easy way to automate this assessment. Smartphone applications, such as Runmatic

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\begin{table}
\centering
\caption{Clinical and Field assessments for RTP after ACLR in soccer players}
\begin{tabular}{|l|l|}
\hline
\textbf{Clinical Assessment} & \textbf{Hop Tests} \\
\hline
Running & Proprioception and Balance \\
Graft Laxity Test & Psychological \\
Isokinetic Test & \\
Vertical Force – Velocity Profile & \\
\hline
\textbf{Field Assessment} & \\
Game Simulation & Repeated Sprint Ability \\
Dual Task & Work Load during game simulation \\
Deceleration & Agility Tests \\
Fatigue after game simulation & Horizontal Force – Velocity Profile \\
\hline
\end{tabular}
\end{table}
(Runmatic App, Dr. Carlos Balsalobre-Fernández), can also provide an overview of the symmetry of the gait parameters (lower limb stiffness) with a recording of eight steps.

After a warm-up on the treadmill, a recording of the flight time and the contact time for each step is made during a 30 seconds running sample, at a speed of 12 km·h⁻¹. According to the work of Morin et al., the stiffness coefficient of the lower limb (its global compression during the acceptance of the body weight during the phase of single-limb support) and be estimated.²⁰,²¹

Therefore, strength asymmetry of less than 10% for RTP is proposed as healthy subjects present a strength asymmetry lower than 5%, and preliminary studies have shown an increase in the risk of injury if the strength asymmetry is higher than 10%.

**GRAFT LAXITY TEST**

After a normal clinical examination (no pain, full range of motion, no effusion), a test battery can be conducted. Gokeler et al. highlighted the use of a robotic laximeter as a tool to determine one assessment for RTP.²² Too much tibial anterior translation can increase ACL injury risk.²² In addition, graft healing is long time process (approximately 2 years)²³ and it is important to be able to assess graft laxity using reliable tools. Lachmann, Pivot Shift, and direct anterior drawer tests are commonly utilized, but robotic laximeter use shows potential for objective data which can inform RTP decisions. A laximeter is a passive test and establishes dynamic elongation curves by comparison of the two knees (Figure 1). The device automatically calculates displacement and establishes curve slopes. The cut-off value is the difference of 3 millimeters between the knees²⁴–²⁷ at 134 N for a sensitivity of 70% and a specificity of 99%.²⁷ During RTP assessment, three anterior translations at 250 N can be performed. After examination of the differential at 134 N, the slope differential is assessed. It corresponds to the functional instability risk, which should not exceed 10 μm·N⁻¹. For a result with regard to RTP, we set the differential at 134 Newton to less than or equal to one mm and a slope differential less than five μm·N⁻¹.²⁸–³⁰

**ISOKINETIC TESTING**

Although strength tests were reported in only 41% of the studies that describe RTP criteria,³¹ strength assessment, especially of the quadriceps, is of high importance. Quadriceps strength is correlated with i) functional test performance,³²,³³ ii) self-reported outcomes³⁴,³⁵ and iii) risk of reinjury.³⁶,³⁷

Strength assessments are performed in different modes (isometric, isokinetic: concentric or eccentric) and various angular speeds. If no standardized protocol is used following ACLR,³⁸ most researchers use concentric peak torque of knee extension and flexion at 60°/s, normalized to body weight (PT60/BW).³⁶,³⁷,³⁹–⁴¹ The Limb Symmetry Index (LSI) expresses the performance of the operated side as a percentage compared to the contralateral side. The goal is generally to achieve a PT60/BW-LSI greater than 90%,³⁶,³⁷,³⁹,⁴² but these values are rarely achieved.³⁸ Additionally, the LSI may overestimate the capacities of the operated limb, if the healthy limb is detained.⁴³ Therefore, clinicians should assess both LSI and reference values.⁴⁰

The ratio of hamstring and quadriceps peaks (Hamstring/Quadriceps ratio) is not a functional ratio, since it compares peaks appearing at different angles, but it is correlated with the risk of injury.⁵⁷

The single PT60/BW value analysis could lead to a loss of information, which is why studies should focus on the torque profile specific to the angle of knee flexion,⁴⁴ in order to improve understanding of the deficits identified, and therefore guide rehabilitation.

Since speed and absorption capacity are necessary for most physical activities, especially when changing direction and jumping,⁴⁵ Edouard et al. suggest testing using faster speeds and the eccentric isokinetic mode.⁴⁶ Concentric mode isokinetic assessments cannot assess the differences in rate of force development of the muscles.⁴⁷

Authors criticize the use of isokinetics for strength assessment because of the gap between this mode of assessment and real life, such as analysis of a single motion in a single plane in contrast to the complexity of sports movements. That movements carried out in an isokinetic manner do not approximate the movements that occur in normal activities (isokinetic speeds described as `fast’ do not exceed 300°/s, when certain movements, like sprinting, are performed at a much higher speed). Finally, open kinetic chain testing of muscles usually used in closed chain functional tasks has been discussed.⁴⁶ Biomechanically, this assessment is the measure of the force couple, in a single plane, which we know to be different in vivo.⁴⁶

This evaluation nevertheless remains the gold standard, but other methods of evaluating neuromuscular performance are being studied. These methods, like force platforms, are to be more functional.

**HOP TESTS**

Hop tests are designed to assess lower quarter function after ACLR and other surgeries and conditions. While some authors have shown good methodological quality for these tests, their validity has been challenged. According to Kotzifaki et al., knee performance is better assessed during landing and not during propulsion, particularly on Single Hop Test (SHT).⁴⁸–⁵¹ Similar validity issues are observed on Triple Hop Test (THT), especially during the concentric propulsion phase where there can be hip, pelvis and trunk compensations.⁵⁰ Thus, according to Kotzifaki et al. the LSI obtained during vertical jumps seems to demonstrate knee function deficits more accurately than horizontal jumps.⁴⁹

The quantitative measure of the horizontal jumps to represent lower limb systemic performance which is essential for RTP.

For a qualitative assessment, use the qualitative analysis of single leg score (QASLS) to evaluate the landing and provide feedback on knee function.⁵² Indeed, dynamic valgus associated with an increase in the knee abductor moment constitutes a very important risk factor for ACL re-injury as shown Paterno et al.⁵³ During landing test, Hewett et al. highlights a sensitivity of 77% and a specificity of
81% when dynamic valgus appears within the initial 10% of landing.11

Before a more ecological evaluation, the authors recommend assessing the knee on horizontal (SHT, THT), vertical (Single Leg Vertical Jump) and multidirectional (30 cm Side Hop Test, Cross Over) directions. According to the literature, the LSI must be at 90% and the QASLS < 1 in search of an increase in the knee abductor moment.37,52–54

Furthermore, it is important to be able to determine plyometric qualities and coordination in bipedal and unipedal modes (Table 2). Regarding coordination, assessment with the countermovement jump (CMJ) and Abalkov Test can offer information. A difference greater than 6 cm must be found in order to determine good coordination. Regarding plyometric qualities, it is important to perform both the squat jump (SJ) and drop vertical jump (DVJ). The difference should not be below 6 cm. A difference that exceeds 10 cm demonstrates good plyometric qualities. Plyometrics are an essential asset in ACL re-injury prevention.55–57 With the DVJ, we can also calculate the reactive strength index (RSI) which shows the ability of the knee to store and restore energy. According to Flanagan et al., it must be greater than 2.5 in order to show good plyometric quality.58

Table 2. Assessment of coordination, plyometrics and reactive strength indexes

<table>
<thead>
<tr>
<th>Index</th>
<th>Tests</th>
<th>Cutoff values</th>
</tr>
</thead>
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<tr>
<td>Coordination</td>
<td>Abalakov – CMJ</td>
<td>&gt; 6 cm</td>
</tr>
<tr>
<td>Plyometric</td>
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<tr>
<td>Reactive Strength</td>
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<td>&gt; 2.5</td>
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</tbody>
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CMJ; Countermovement Jump, DVJ; Drop Vertical Jump, SJ; Squat Jump

PROPRIOCEPTION AND BALANCE

Without vestibular disorders, proprioceptive alterations can be assessed via stabilometric analysis which can be performed in bipedal and unipedal modes, with vision or without.

Evaluation of static balance can be assessed by the study of mobility and variations in the center of pressure (CoP) which allows the quality of global proprioception and postural adaptation to be described. Using a stabilometry platform offers the possibility of calculating the Romberg quotient according to Ruhe et al.,59 which quantifies visual dependence in bipedal and unipedal conditions. Visual dependence occurs when a perceptual conflict between different sensory inputs occurs, giving precedence to visual input and creating difficulties in changing frames of reference using vestibular and proprioceptive afferents according Lubetzky-Vilnai et al.60 The Romberg quotient is calculated by the ratio of the surface of the ellipse containing 90% of the points of the center of pressure with eyes closed to that with eyes open; it quantifies the importance of visual input and therefore the importance of vision in postural control. The result is physiologically close to 93% (eyes closed CoP displacement / open eyes CoP displacement; multiplied by 100) with a difference with a standard devi-
ation of 20%.\textsuperscript{61} To overcome this visual dependence, stroboscopic glasses use associated with visual-motor training has demonstrated effectiveness in reducing reaction time in particular, as well as improving muscle coactivation and muscular anticipation, which then may reduce ACL injury risk.\textsuperscript{62–66}

Dynamic balance should also be assessed, for example, by the Star Excursion Balance Test modified\textsuperscript{67} or Y-Balance Test. These two tests are also a reliable way to be able to predict lower limb and ACL injury risk. Lee et al. found a strong correlation with knee flexors strength and hip abductors strength.\textsuperscript{68} Furthermore, Pilsky et al.\textsuperscript{69} reported that an asymmetry of 4 cm in the anterior distance indicates a high risk of injury to the lower limb that there was a 3.5 times higher risk of injury in the event of a symmetry of less than 90%.

PSYCHOLOGICAL ASSESSMENT

If injury and surgery lead to significant physiological changes, there are psychological considerations, in particular apprehension and confidence, which impact RTP. Paterno et al. showed that athletes with a poor Tampa Scale Kinesiophobia 11 score (19 or more) have a risk factor multiplied by 13 for secondary ACL tears within two years after RTP.\textsuperscript{70} Straub et al. described a positive correlation in male athletes between symmetrical quadriceps strength and psychological aspect upon RTP.\textsuperscript{71} Similar results were reported by Webster et al. and Kim et al. who showed a correlation between symptoms, function, and psychological status at RTP.\textsuperscript{72,73}

In the authors’ opinion, the Anterior Cruciate Ligament-Return to Sport after Injury (ACL-RSI) is the best way to assess psychological qualities of the player during RTP. Langford et al. suggest that it is possible to identify athletes at risk of no RTP for psychological reasons after ACLR.\textsuperscript{74} Ardern et al. highlight that psychological variables measured with ACL-RSI are the only predictors of RTP before injury.\textsuperscript{75} Therefore, it is important to be able to detect the risk profiles of players who are overconfident in their RTP when compared to their physiological qualities. Conversely, specific psychological preparation for RTP can be initiated if the ACL-RSI score is not satisfactory. Kitaguchi et al., during an evaluation at six months after ACLR, shows ACL RSI cut off values of 81.3% (sensitivity = 0.8 and specificity = 0.6) and a score of 55% (sensitivity = 0.69% and specificity = 0.82) as a predictor of RTS at one year.\textsuperscript{76}

VERTICAL FORCE – VELOCITY PROFILE DURING A SQUAT JUMP

Samozino et al.\textsuperscript{77} relied on Newtonian dynamics laws to create a mathematical equation that allows the calculation of the values of force, speed and power using the following values: body mass, jump height and lower limb extension distance when pushing. It then becomes easy to obtain a reliable estimate of the force-velocity-power relationship of the lower limbs as well as the tracing of the individual force-velocity profile using data from a force plate. The athlete must perform a SJ with body weight alone and add 20% of body weight to each vertical jump. The test stops when the player cannot jump more than 10 cm. (Figure 2).

The profile which is created is compared with a theoretical optimal profile. For a maximum power value, there must be a balance between the qualities of force produced during the jump and the speed at which the jump is made, thus allowing optimization of performance. If the slope of the measured force-velocity line is greater than the slope of the optimal profile, it is necessary to focus on force production. Conversely, if the slope measured is lower than that of its optimal profile, then training must be focused on the development of velocity.

THE SECOND STEP: FIELD (FUNCTIONAL TESTING)

GAME SIMULATION

Welling et al.\textsuperscript{78,79} highlighted the fact that RTP tests are often not administered in a sport-specific environment. For example, it is uncertain whether performance during hop tests can be transposed to a sport-specific situation in which a patient must react to opponents, teammates, and the ball. Indeed, the actions of dual-task, taking information, processing and decision-making, the specific movements in dual-task, work/performance in a fatigue condition, or even the execution speed of specific gestures are parameters that must be observed during the RTP. However, assessments have many limitations related to the validity and reproducibility of potential tests. To address these issues, the authors have empirically chosen to use a match simulation type session for 45 minutes where the soccer
player reproduces the game demands according to position and level of practice or directly with group of players.

The use of such an observation for the position and the level of the player does not allow a high reproducibility of this session, hence this approach is not used as a "test". During these 45 minutes, the values of acceleration, deceleration, change of direction, jump, tackle, contact, ball handling skills, high speed running (between 14,4 km/h and 19,8 km/h), very high speed running (between 19,8 km/h and 25,2 km/h), and sprint (with acceleration and deceleration) are assessed according to the athlete-specific references. During these 45 minutes, we evaluated only the most intense 5 minutes, period with the greatest density of activities during a session (bount of sprint, acceleration, braking...). A quantitative and qualitative analysis is carried out through GPS tracking and a biomechanical study of movement control (with videography) during dynamic movements (cutting, braking, sprinting, landing jumps).

The authors acknowledge that this assessment has limits, however, it has the advantage of estimating the soccer player's ability to perform the specific demands that await them when returning to the team.

REPEATED SPRINT ABILITY (RSA)

Metabolic energy reserves are essential during recovery. Indeed, the athlete's physiological abilities will impact the quality of RTP. The RSA test represents a reliable assessment that can be adapted to the majority of team sports. This test assesses the athlete's ability to repeat maximum efforts with quality by measurement of the difference between the ideal performance area and the actual area (distance and volume) of the RSA achieved. The maximum speed the player achieves can be quantified via GPS. In addition, there is a strong correlation between the result of the RSA Test and VO2max and the athlete's oxidative power, a key performance factor in soccer. In the literature, the results of this test are between 6 to 12 efforts of 20 to 40m with 30 seconds of recovery.

DUAL TASK

Optimal training of an athlete will assist the player to evolve from a situation with control to a situation where they will readily adapt to chaotic environments. Need another sentences here, about how one gradually increases the chaos? (before you get to the "last stage"......),The last stage (maximum chaos) is divided into two parts with partial integration into the team and then full integration into the team environment. This is an essential moment in the rehabilitative process because cognitive demand is very high. The athlete will be required to manage their own body in space but also the ball, teammates, opponents, and instructions from the coach. This increasing cognitive load can disturb the neuromotor control of the athlete if the motor patterns are not automatic. This is especially important during movements that require deceleration, cutting or landing, commonly occurring during sequences of play with high uncertainty, such as a defensive or pressing situations. A loss of biomechanical quality of knee valgus control or trunk lateral flexion can be directly related to an increased risk of ACL injury.

It is important to put the athlete in a situation of dual tasks and to assess the quality of movement. If major deterioration occurs during dual-task conditions, what will happen in a complex cognitive context as indicated above? This concept is therefore considered during match simulation (during cutting with uncertainty, 1 vs 1), as well as via the single limb landing test with impaired visual input. This is a first level of assessment of the cognitive aspect related to the dual task, information processing and decision-making. However, it must be noted that the level of complexity of the proposed analysis tasks is lower than the multiple cognitive demands that occur during a game situation.

WORKLOAD

To optimize recovery, the athlete's ability to support the daily and weekly training loads of their competition group and her/his position should be highlighted. Indeed, it is recommended that to optimize the RTP and athlete should be able to support approximately 90% of the workload of the highest load of the highest session workload of the week of their training group. This is the athlete's ability to progress group training while maintaining both the quality of neuromotor control during dynamic movements in the game, acceleration levels, speed, and the quantitative aspect related running distances and training intensity.

There are many methods for workload assessment. The Foster method is the most common for evaluation of the internal load. Regarding the external load, GPS analysis is the most commonly used measure, assessing the number of acceleration, deceleration, cutting, and jumping tasks that occur, as well as distances covered at the various speed intervals.

DECELERATION

Current video analysis studies of ACL injuries have identified pressing and tackling as the most common patterns for ACL injury in soccer. Pressing is a situation that leads to the demand for sudden deceleration. It seems important to assess the biomechanics during decelerations, in particular kinematics hip adduction and knee abduction.

However, there is a difference between the literature and clinical practice, as most authors analyze the biomechanics of deceleration using a force platform integrated into the ground and several cameras. Such analysis is not possible on the field of play. It is possible to measure this deceleration via GPS revealing the intensity and distance of the athlete's braking. Fortunately, latest generation smartphones can collect slow motion from 120 to 240 frames per second. The biomechanical analysis can then be performed with free software such as Kinovea®, whose reliability and validity have been demonstrated.
AGILITY TESTS

It is commonly advised to assess the movement qualities during specific movements. There are agility tests for this: the Modified Illinois Agility Test, the AFL Agility run test, the T-test, the Reactive shuttle agility run, the new curve sprint test, and the zigzag agility run, for example. Each of these tests involves analysis of the athlete’s ability to express their neuromuscular capacities in a context of dynamic movement with greater specificity to their discipline and to the demands they will encounter during RTP. The T-test requires acceleration, in particular the rate of force development, which is the quality most impacted by ACL injury, but also the ability to make 90° cuts and backpedal at maximum intensity while maintaining postural control.

The new curve sprint test (Figure 3) is similar to the sprints found in team sports and in particular in soccer, which requires asymmetrical movement of the athlete at maximum intensity, knee-trunk control, and contributions of the ankle-foot complex. Researchers have shown that during soccer game, players mainly repeat sprints of less than 10m but more than sixty times. Caldebeck showed that sprints were rarely in a straight line, but in 85% of cases curvilinear. Hence, to once more closely approximate the reality on the field, the authors recommend the use of a test recently developed by Filter et al. called the curve sprint which is characterized mainly by its reliability, specificity and simplicity, it can be performed easily and precisely in the arc of the penalty area, within a radius of 9.15m and over a distance of 17m. The athlete must perform two sprints in one direction then two sprints in the other direction.

Figure 3. The new curve test sprint

FATIGUE

Van Melick et al. highlighted a reduction in quality of jumping tests which under fatigue conditions and is seen in athletes who had ACLR compared to healthy subjects. Studies are contradictory concerning the role of fatigue in the risk factors of ACL injury; however, it may be important to assess the player under fatigued and non-fatigued conditions. A significant deterioration in quality and/or performance with fatigue should at least inform the professional regarding the athlete’s current ability to RTP at the same intensity as before the injury. Therefore, the authors recommend carrying out hop tests on the field in an ecological condition. The landing test should be performed with a force platform in a non-fatigued state and then in a fatigued situation after the training session including RTP and agility tests. These landing tests are each time carried out in single and dual task conditions. The impact of fatigue can also be analyzed during a game simulation, both from a qualitative (neuromotor control of movement) and quantitative (activity intensity) point of view.

HORIZONTAL FORCE - VELOCITY PROFILE

Sprint force-velocity profiling is a subject of growing interest to inform the RTP, especially in soccer players. These profiles may contribute strongly to the production of the horizontal component of the reaction force on the ground and therefore influence the lower limb theoretical maximal force (F0) capabilities. Mendiguchia et al. found a decrease in maximum horizontal power with an ability to produce force at the start of the acceleration phase, 20% deficit after injury while the value of F0 was almost unchanged. These authors have hypothesized that this deficit could be the cause of mechanical overload in the hamstring. Therefore, players who have ACLR with a hamstring graft should benefit from this assessment.

Soccer players must sometimes combine running at high speed with a non-linear trajectory, for example while driving the ball and cutting. Baena-Raya et al. were interested in the potential relationship between the variables of the individual force-velocity profile and the ability to
cut. They report that the variables F0 and the lower limb maximal power (Pmax) capabilities were strongly associated with performance during changing direction in soccer. These authors showed that the ability to orient the ground reaction force vector horizontally (RFmax) was associated with enhanced performance on cutting tests.

**IS NEUROMOTOR CONTROL THE KEY?**

External and internal pressures may include a combination of spatiotemporal constraints, differing levels of cognitive complexity, and fatigue. These scenarios will impact the athlete’s ability to execute a movement task effectively and may also predispose them to positions associated with heightened injury risk. During the most intense and demanding moments on the field, athletes may only have milliseconds to scan the surrounding environment and decide upon and execute an appropriate movement.

Perceptual and cognitive load must be viewed with the same level of importance as the physical components of performance toward which the rehabilitation professional devotes much rehabilitation time.

Optimal movement technique and appropriate training load are important in both the gym and on the pitch, and the focus should not solely be on reaction and response time, but rather also include accuracy and error rate (inappropriate execution of movement in response to a specific stimulus) Monitoring an athletes’ agility success rate during progressively greater game-like training scenarios may provide practitioners with an enhanced appreciation of the player’s readiness to train; this is also an important avenue for future research. The effect of motor task difficulty on cognitive performance as an error rate can be masked with a delay in reaction time and can increase injury risk for the athlete. Therefore, simultaneous assessment of reaction time and error rate can provide a broader understanding with regard to cognitive effects on performance during complex tasks that require dual tasking, which present in most, if not all sports.

A greater number of decision-making scenarios and shorter time periods to react to those decisions are some examples that might contribute to ACL injury and should be considered by clinicians after surgery, during rehab scenarios. Future research into injury mechanisms should also consider the contextual factors surrounding the injury to ensure the chaotic complexity of match play is at the forefront of discussion.

**CONCLUSION**

Clearly, strength, neuromotor agility, psychological, and cardiovascular fitness are required for a safe RTP, and authors have suggested that ecological situations used to study these parameters are important to implement. Novel concepts are highlighted regarding assessments for both clinical and field measurement use, which together capture a more complete picture of neuromotor control in the athlete. Neuromotor control is crucial in terms of the quality of movement, whether during specific and analytical tasks, or tasks with cognitive load, and those that occur in a situation of fatigue. Assessing facets of neuromotor control in standardized or ecological situations with reproduction of the cognitive load required during participation is key to a safe RTP.

**COI STATEMENT**

The authors declare that they have no competing interests.

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Clinical Commentary/Current Concept Review

Periodization in Anterior Cruciate Ligament Rehabilitation: New Framework Versus Old Model? A Clinical Commentary

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Keywords: periodization, motor control, anterior cruciate ligament reconstruction, return to sport, cognitive phase/mesocycle

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The physiological and psychological changes after anterior cruciate ligament reconstruction (ACLR) do not always allow a return to sport in the best condition and at the same level as before. Moreover, the number of significant re-injuries, especially in young athletes should be considered and physical therapists must develop rehabilitation strategies and increasingly specific and ecological test batteries to optimize safe return to play. The return to sport and return to play of athletes after ACLR must progress through the recovery of strength, neuromotor control, and include cardiovascular training while considering different psychological aspects. Because motor control seems to be the key to a safe return to sport, it should be associated with the progressive development of strength, and cognitive abilities should also be considered throughout rehabilitation. Periodization, the planned manipulation of training variables (load, sets, and repetitions) to maximize training adaptations while minimizing fatigue and injury, is relevant to the optimization of muscle strengthening, athletic qualities, and neurocognitive qualities of athletes during rehabilitation after ACLR. Periodized programming utilizes the principle of overload, whereby the neuromuscular system is required to adapt to unaccustomed loads. While progressive loading is a well-established and widely used concept for strengthening, the variance of volume and intensity makes periodization effective for improving athletic skills and attributes, such as muscular strength, endurance, and power, when compared with non-periodized training. The purpose of this clinical commentary is to broadly apply concepts of periodization to rehabilitation after ACLR.

INTRODUCTION

Non-contact injury of the anterior cruciate ligament (ACL) is a common sports-related injury typically warranting extensive rehabilitation time and reconstructive surgery followed by rehabilitation. After a sports injury, the first question asked by most athletes (and coaches) is: ‘When will I (the athlete) be able to compete again?’ The answer to this question is rarely straightforward and is influenced by many factors. However, in most cases the goals of the injured athlete and the treating clinician (plus other stakeholders in the decision-making team, such as coaches, parents, and managers) are the same—to facilitate a timely and safe return to sport.1

Athletes that return to play are at an elevated risk for re-injury or injury to the contralateral limb with an estimated 1 in 4 (25%) athletes suffering a second injury after returning to high-level sport.2 The high re-injury rate among injured athletes has been a focus for researchers attempting to identify modifiable risk factors and different rehab protocols according the graft choice, type of surgery, type of injury (meniscus or medial collateral ligament, involve-ment, etc.) for rehabilitation strategies to improve return-to-sport (RTS) outcomes.3 Periodization is probably one of the most important and fundamental concepts in training and it is important to consider the use of this concept in rehabilitation of injuries to the ACL and after ACL reconstruction (ACLR).4 Periodization consists of a ‘training cycle’ divided into different training or rehab phases with distinct physical and physiological objectives – to enable the best performance from athletes in competition (i.e. peak performance, injury prevention). Theoretically, using the periodization concept, peak performance is achieved in a controlled way, as a result of the summation of the particular adaptations provided by each training-rehab phase (mesocycle; Figure 1).5

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Various models of periodization exist. The two most common are linear and non-linear. Linear periodization adjusts exercise volume and load across a series of predictable phases or mesocycles. This stepwise progression from one training stage to another based on intended goals is similar to advancing a rehabilitation protocol from one stage of recovery to the next. Non-linear periodization, on the other hand, involves a more frequent change of volume and load within a mesocycle.

However, when examining the role of the use of the periodization concept in achieving the maximum specific performance in selected sports events (e.g. a season’s best result), an important drawback emerges: very low rates of effectiveness.

The high frequency of competition, together with the increasing physical demands of competition over the season, has served to accentuate the physical and mental load incurred by elite athletes from different sports. As a consequence of these demands, the importance of recovery and rehabilitation strategies designed to alleviate player fatigue, minimize injury risk, and enhance performance is of paramount importance to clubs and national federations responsible for managing the elite player health.

The use of periodization in long standing rehabilitation programs after ACLR needs more research and data to become accepted by health professionals. Therefore, the purpose of this clinical commentary is to broadly apply concepts of periodization to rehabilitation after ACLR.

CAN PERIODIZATION BE APPLIED IN LONG-TERM REHABILITATION, SUCH AS AFTER ACL INJURY?

Over the years, the pursuit of greater human performance through training has led to athletes, coaches, and physical therapists engaging in higher training volumes and often greater intensity. When coupled with ever increasing competition demands and fixture congestion the interest in exercise recovery strategies is extremely important to consider within the training and competition calendar. Rehabilitation programs have traditionally used a basic progressive overload approach primarily focusing on the injured area. Periodized training is a safe method of training for healthy athletes, as well as those in pain or following an injury. The ideas and concepts presented in this commentary have not been tested in randomized controlled trials, however they may stimulate further suitable studies investigating the application of periodization in rehab.

Periodization is the planned manipulation of training variables (load, sets, and repetitions) to maximize training adaptations while minimizing fatigue. Periodized programming utilizes the principle of overload, whereby the neuromuscular system adapts to unaccustomed loads. While progressive overload is a well-established and widely used concept for strengthening, the variance of volume and intensity makes periodization effective at improving athletic performance attributes, such as muscular strength, endurance, and power, compared with non-periodized training.

The traditional periodization model assumes that a relatively prolonged period of basic training/rehab (general preparation / rehabilitation stages) is a prerequisite to a more specific phase (special preparation / cognitive phase). During general preparation, rehabilitation specialists aim to improve cardiorespiratory endurance and strength, even in athletes competing in power-speed sports disciplines.

Another common belief related to strength-power development, is that the so-called ‘strength foundation phase’ will provide positive transfer of maximum strength to the ability to produce muscle power in the subsequent training phases or rehab stages. To date, there is no strong evidence supporting this belief, mostly held in traditional literature written on the basis of authors’ personal experiences and not supported by research. Conversely, there are studies showing that training using heavy-loads (i.e. maximum strength training) results in improvements only in the high-force/low-velocity portion of the force-velocity curve, without necessarily affecting the ability to produce higher amounts of force at high velocities (muscle power). It appears that the parametric relationship between force and velocity (i.e. the higher the load, the lower the velocity) plays a key role in modulating chronic neuromechanical adaptations and may be helpful in preventing re-injury.

For instance, in endurance sports, athletes appear to benefit from performing high volumes of low-intensity training (i.e. below lactate thresholds) during their basic/specific periods of preparation. Furthermore, coaches and physiotherapists use prolonged periods of basic training on muscle-tendon tissues adaptation and injury prevention cannot be ignored. However, it is likely that these positive adaptations in muscle, tendons and ligaments may also be obtained by typical strength power exercises, which can be directly implemented during the course of a rehab period.

PERIODIZATION CONCEPTS DURING ACL REHABILITATION: PRACTICAL APPLICATIONS

The initial post-operative phase of ACLR rehabilitation focuses on pain and swelling management, restoration of range of motion, quadriceps recruitment, and normalizing gait mechanics. Once an athlete meets these goals, they can begin a periodized resistance training program. To determine the appropriate load for an exercise prescription, clinicians must establish a one-repetition maximum (IRM) for each exercise. Injured or healing tissues pose a challenge
to determining IRMs when they require limited loading. Indeed, for most sports disciplines, make it extremely difficult for strength and conditioning coaches and physical therapists to adopt this classic and theoretical method used with healthy athletes to those recovering from injury or surgery.

The injury-induced reduction in physical and mental function associated with sports training and competition infers that it is illogical that a single recovery strategy and/or a generic one-size-fits-all approach would address a player’s recovery requirements. Alternatively, a framework where strategies are sequenced systematically at independent time points to match the source of physiological stress, alongside consideration to favorable adaptation might be a preferred approach in sports.

From a practical standpoint, monitoring athletes using a battery of tests (Y-Balance test, hop tests, etc.) which best correlate to actual sports performance and RTS after injury is much more important than following theoretical concepts, which subjectively state that form might be predictable and controlled. With this simple and applied thought, strength and conditioning coaches and rehabilitation specialists may select better ways to control fluctuations in the competitiveness of individuals and teams, in addition to the already well-established variations in traditional training components (i.e. volume and intensity). Monitoring will help physical therapists and coaches to detect unexpected adaptations in the athletes’ fitness traits and adjust rehab and training loads according to these measured responses. In this regard, the use of validated methods for daily assessment (like GPS) of the internal training loads might be a useful strategy to quantify/modulate training intensity and its respective dose-response relationship with the specific changes in physical and mental qualities and quantities (cognitive load and fatigue assessment).

THE NEUROCOGNITIVE MESOCYCLE: THE MISSING LINK IN ACL PERIODIZATION

ACL rehabilitation is a complex and multifaceted process involving physiological and psychological parameters which need to be constantly evolving to optimize individual athlete recovery needs and physiological adaptation. The relative importance of recovery versus adaptation will vary according to the needs of the athlete within the context of the procedure. This raises the idea of using rehab strategies in a manner that is periodized to mirror the demands of the sport, and to adequately recover from the stress, but also consider the need for an adaptive response. Sports injury rehabilitation must move beyond the traditional emphasis on mechanics and muscle strength and consider the need to address nuanced sensorimotor control deficits to ensure complete recovery and readiness for RTS demands. ACL injuries during sport are predominantly non-contact, suggesting injury may be a product of sensorimotor errors that result in a neuromuscular control fault unable to accommodate deleterious joint loading. Further, the vast majority of non-contact injury events occur while athletes are cognitively distracted, attending to complex visual demands or environmental stimuli, suggesting that neural mechanisms may directly contribute to the athlete’s ability to safely interact with the dynamic sport environment. Neurocognitive tasks, such as those measuring reaction time, processing speed, visual memory, and verbal memory, are well established in the neuropsychology literature as indirect measures of cerebral performance.

Situational awareness, arousal, and attentional resources of the individual may influence several areas of neurocognitive function, affecting the complex integration of vestibular, visual, and somatosensory information needed for neuromuscular control. Neuropsychological deficits following ACL injury and surgery may at least in part be caused by physiotherapy protocols that do not engage differential learning and dual-tasking during (engaging more demanding aspects of the cognitive arsenal) exercises.

Over the course of rehabilitation following ACLR, excitability of the motor cortex for quadriceps contractions decreases, at least partially from the lack of differential exercise approaches that do not force the motor cortex to reintegrate the memory trace for quadriceps motor control before each repetition and action. Neurophysiological data across the stages of rehabilitation are lacking. Neuroimaging has been used to quantify brain activation differences between subjects with ACL deficiency who did not return to previous levels of physical activity and a healthy control group. In this phase, patients will focus on sport-specific exercises that are intended to be extremely challenging both physically and cognitively while performed in a controlled environment. All of the previously mentioned multimodal tasks can be implemented with a major focus on motor learning, cognitive loading and sensory re-weighting that are real-to sport and require quick decision making from unanticipated events.

CONCLUSION

Sports rehabilitation specialists especially physical therapists and sports medicine physicians should have a basic understanding of periodization theory. Such an understanding can help sport medicine teams to better interact with the competitive mindset of athletes, their coaches, and their goals. A basic understanding of periodization theories and models may help sports rehabilitation specialists to skillfully plan rehabilitation programs that then progress toward the realization of the patients’ treatment goals.

With recent evidence in support of neurological contributions to ACL injury and rate of recovery, rehabilitation protocols may benefit from incorporation of approaches that target the sensorimotor and cognitive system. Periodization can incorporate the integration of motor learning principles (external focus and differential learning, anticipation, and reaction) and/or new technologies may bolster current ACL rehabilitation protocols and improve patient recovery and timing. Research has traditionally focused on administering a single rehab intervention whereas, in the applied setting, athletes are more likely to administer mul-
Multiple interventions in varying sequences. Future research using robust rehabilitation technique protocols and large-scale randomized control trials is needed to better understand the influence of various techniques and the application of periodization concepts on the stress-injury-adaptation continuum.

CONFLICTS OF INTEREST
The authors report no conflicts of interest.

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ABSTRACT
As physical therapists, understanding the anatomy and biomechanics of the musculoskeletal system is essential for accurate diagnosis and effective treatment outcomes. Musculoskeletal ultrasound (MSK-US) is one tool that has revolutionized the way physical therapists evaluate musculoskeletal pathology. Specifically, assessing the ulnar collateral ligament (UCL) proves especially beneficial for providing both diagnosis and treatment planning. By directly visualizing static and dynamic loads to the ligament, physical therapists can gain valuable information about underlying pathology and guide the therapeutic decision-making process. In this sound byte, we will look at how incorporating MSK-US imaging into your patient assessments can provide you with more comprehensive data to make informed clinical decisions when treating UCL injuries in the elbow.

PATIENT POSITION

Figure 1a: Patient Position.
Supine with the involved arm abducted to 90 degrees, elbow flexed to 60-90 degrees and maintained in full external rotation. A bolster or towel under the arm applies a passive valgus stress to the elbow placing strain to the UCL ligament. The Green Box outlines the oblique longitudinal/LAX position of transducer.

TRANSDUCER PLACEMENT

Figure 1b. Transducer Placement.
The transducer is placed in an oblique longitudinal/LAX position. The probe needs to be anterior to the medial epicondyle to visualize the targeted UCL. This LAX position will be used to view either the anterior or posterior bands.

Figure 1c: Transducer Placement with Valgus Stress Applied.
With the probe in place, the arm can be rotated back into external rotation with a bolster or towel under the elbow where the valgus stress is reapplied. This exam becomes a dynamic assessment showing the UCL laxity in real time.
Figures 2a and 2b:
The normal anterior band of the ulnar collateral ligament is located by finding the hyperechoic bone contour of the medial epicondyle. The ligament is deep to the adjacent flexor tendon. The ulnar collateral ligament will appear hyperechoic and fibrillar. The humero-ulnar joint space must be visible for dynamic testing of the ulnar collateral ligament integrity.

Incorporating musculoskeletal ultrasound in the diagnosis of UCL injuries
The diagnosis of UCL injuries can be complex; however, musculoskeletal ultrasound (MSK-US) is a useful and effective, noninvasive imaging modality for evaluating the UCL of the elbow due to its simplicity and convenience. Since MSK-US is not a radiation-based technology, its use is generally safe and painless for patients. Coupled with fast results and a smaller risk of complications, MSK-US is quickly becoming the go-to imaging method for diagnosing soft tissue issues such as ligament or tendon tears in the elbow region.

MSK-US offers several benefits compared to other imaging modalities in the diagnosis of elbow injuries making it increasingly easier to identify and diagnose UCL tears and other similar pathologies. MSK-US can provide instant real-time images during an examination, allowing examiners to accurately identify and grade any tear that may have occurred due to overuse, trauma or congenital anomalies. The common imaging findings associated with these conditions can be grouped into three distinct categories of MSK-US findings: tendinopathy, discontinuity of the ligament/tendon substance, and foreign bodies such as small particles of debris.

When evaluating a UCL tear with MSK-US, one may observe a widened UCL or redundant folds, irregular hyperechoic structures, clefts or gaps in the ligament coaptation line, discontinuity of continuous fibers within the UCL fibers, or pseudo fluid collections at some locations with laxity. Discontinuity appears as an apparent tear or reciprocal function with the anterior band being tight in extension, while the posterior band is tight in flexion. Attenuation or rupture of the UCL can result in valgus instability.

Exploring the diagnostic criteria for various UCL injuries
There are three main types of UCL injury: partial tear, complete tear, and avulsion fracture. Partial tears are further classified into either grade 1 or grade 2, depending on the severity of the injury. Grade 1 tears are small tears or fraying of the ligament, while grade 2 tears are more significant tears with some loss of function. Complete tears are when the ligament is completely torn, and avulsion fractures occur when a small piece of bone is pulled away from the bony attachment along with the ligament.

The diagnosis of UCL injury relies on an accurate history and physical examination. Clinicians must consider several factors when diagnosing UCL injuries, such as activity level, history of any prior injuries, and the individual’s presenting symptoms. Typically, patients with UCL injury will present with either acute or chronic onset of medial elbow pain. Symptoms of UCL injuries include pain and tenderness on the medial side of the elbow, swelling, loss of range of motion, and weakness in grip strength. Physical examination can often reveal crepitus (grating or grinding sensation) and joint line tenderness with palpation. Provocation testing can further localize the symptoms to the medial elbow. Particular attention should be given to ensuring that no other underlying condition is present when diagnosing a UCL injury. Imaging studies such as static radiographs, stress radiographs, and magnetic resonance imaging (MRI) can be helpful in making the diagnosis.
gap between the proximal and distal ends of the
tendon/ligament with intra-tendinous hyperechoic areas.
A high-resolution MSK-US image can also reveal other
pathologies such as tendinopathies, swelling, joint
effusions, and cartilage lesions. Tendinopathy consists of
irregular fibers within affected muscles or tendons and
occasionally thickening around the tendon which may
present with hypoechoic regions. Debris in a joint space
indicates foreign bodies such as bacteria or nutrient crys-
tals which can cause inflammation and damage to the sur-
rounding tissue. MSK-US can help differentiate these
pathologies from chronic disruptions such as UCL tears or
instability events. By accurately isolating these imaging
findings together with the history and physical examina-
tion, MSK-US can safely diagnose and monitor muscu-
loskeletal disorders providing accurate guidance for treat-
ment options.

Technical considerations for musculoskeletal ultra-
sound examination of the elbow
An MSK-US examination of the elbow requires several
technical considerations to achieve an optimal diagnostic
result. The transducer must be carefully prepared with a
coupling gel and placed perpendicular to the skin surface
for a clear picture of the anatomy. Higher frequency
transducers do not penetrate tissue as well but provide
resolution of a more superficial structure. Scanning during
dynamic movement should also be incorporated when
imaging the elbow, as it can provide more detailed images
essential for diagnosis in a clinical setting. Additionally,
optimize the patient’s position so they feel comfortable
during imaging and the angle of view is maximized.
Following these technical considerations will ensure an
optimal MSK-US examination of the elbow.

MSK-US has become a popular modality for evaluating
UCL injuries due to its advantages of being cost-effective
and avoiding the need for x-rays. Not only does MSK-US
offer advantages over traditional diagnostics methods like
radiology, but its recent advancements have made it even
more efficient and successful in evaluating UCL tears. An
advantage of MSK-US is that it can be used in the outpa-
tient setting without prior preparation, such as an injection
of contrast materials. In this setting, MSK-US provides
excellent imaging of the elbow anatomy which aids in the
accurate diagnosis and treatment of UCL injuries. Because
of its reliability, MSK-US should be considered when diag-
nosing possible UCL tears or other elbow pathologies.