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In 1994, George Davies (a founding father of sports physical therapy), authored an article titled, “The Need for Critical Thinking in Rehabilitation,” in which he described the need for clinicians to apply critical thinking to clinical interventions, using an example of the integration of open and closed kinetic chain exercises in rehabilitation. Dr. Davies observed the predominant use of empirically based clinical experiences more than quality research in guiding clinical practice.

This article formed the basis for my passion to integrate critical thinking in sports rehabilitation as I graduated from physical therapy school that in 1994. Around that time, the concept of “evidence-based medicine” was becoming more popular in rehabilitation: apply the “best evidence” while considering the values of the patient and your clinical experience. This new 3-pronged concept of evidence-based practice seemed to serve as an appropriate model for critical thinking.

Over the following 25+ years of practice as a physical therapist and athletic trainer, my colleagues and I witnessed many trends come and go. It seems that every few years, different treatments become popular and widely utilized only to be replaced by something new (Figure 1).

Over those years, I noticed an interesting paradox of research in clinical practice. While we wanted to have “research” to base our clinical decisions (best evidence), we relied on what worked for us and the patient (clinical experience and patient values). Many treatments without research support gained popularity because clinicians and patients saw results (or saw it used in the Olympics); however, when one research article was published that suggested the treatment wasn't as effective or useful, clinicians quickly abandoned them for the “next shiny object.” This phenomenon was described as “Scott's Parabola” in the British Medical Journal in 2001 to describe the rise and fall of a surgical technique. I've modified the original Scott's parabola (Figure 2) to help explain the rise and fall of common physical therapy treatments in Figure 1.

Unfortunately, this continuous wave of ups and downs leads to inefficiency in rehabilitation, as Silbernagel et al suggested in 2019: “…the hasty implementation of new tools without solid evidence potentially results in extended time and effort to de-implement ineffective management approaches.” In other words, we waste time “un-doing” the unwanted ripple effects from an ineffective treatment.

While my clinical experience grew with time, I realized that the ability to identify the “best evidence” was a continuous process. The process of identifying the “best evidence” was poorly defined, and we often relied on the few professional journals in our field at the time for the best evidence. But today,
how do busy clinicians have the time to find, read, analyze, and integrate the multitude of research articles coming out each month? Ideally, clinicians would be able to keep up with the literature, but we continue to rely on colleagues, gurus, websites, and (gulp) social media to select, interpret, and apply research for us...sometimes in 280 characters or less.

It seems that today, more than ever, rehabilitation clinicians need to be better-informed consumers of the scientific literature. While most clinicians strive to be ‘evidence-based’ practitioners, there are many barriers to incorporating evidence in practice: lack of time, lack of access, and lack of knowledge and skills may hinder clinicians efforts to apply the best-available evidence with patient values and clinical experience. This is compounded by the sheer volume of new research, which includes poor-quality studies with lack of adequate peer review, sometimes published in so-called predatory journals. In addition, misinformation continues to be spread through the profession through advertising and social media, likely due to bias, lack of understanding, or profiteering.

Unfortunately, Dr. Davies' observations about critical thinking in rehabilitation still ring true today. Clinicians still rely on poor-quality studies and “jump on the bandwagon” of today’s “trendy treatments,” while gurus continue to “preach the word about the beneficial effects of certain treatments without any prospective research documentation other than testimonials.” This requires today’s clinicians to take responsibility for overcoming the barriers rather than relying on trusted journals and lecturers for the answers.

Educating clinicians on finding and appraising research for the “best evidence,” and applying to individual patients remains paramount in developing critical thinking in rehabilitation. Today’s rehabilitation professionals should maximize their scientific literacy to support critical thinking. This may begin with the students at professional schools, where more emphasis could be placed on critical thinking and critical appraisal of the literature, as well as the proper application of research findings in making clinical inferences. Practitioners should devote more time to critical appraisal, analyzing original sources rather than relying on secondary sources (ie, “gurus”), stay current by participating in journal clubs, and even participate in clinical research studies.

Although beyond the scope of this editorial, critical appraisal relies on several factors. However, the main factors in quality assessment are presence of bias and confounders, as well as reporting standards. Bias and confounders threaten the internal validity of a study by potentially influencing the outcome and its interpretations. Operationally, bias refers to factors that can be controlled by the researcher through study methodology (recruiting, statistics, etc), while confounders are factors that are inherent to subjects (age, race, gender, etc.) and may be addressed through design or analysis.

External validity refers to the generalizability of the results, but also can be affected by the details reported by the authors in allowing replication of the study. The Equator Network (www.equator-network.org) provides a vast number of reporting standards for various research designs; however, few journals regularly require reporting of these standards (although the IJSPT does require them). Quite simply, we can’t rely on journals alone as the basis for our critical thinking.

Case-in-point: In 2019, a meta-analysis was published in an open-access journal, “Effects of training with elastic resistance versus conventional resistance on muscular strength: A systematic review and met-analysis.” I closely examined the article, finding many discrepancies in the reporting, so much so that I wrote a letter to the editor that resulted in a corrigendum to address each of my concerns over a year later; however, the original article still remains available online with the errors.

I’ve developed the “8-Rs” in applying critical thinking to rehabilitation research. As you evaluate a research study, ask the following questions relative to your clinical question (Table 1, next page):

In conclusion, this editorial is not meant to suggest that everything we do has to have high levels of evidence supporting its efficacy. But we need to apply critical thinking skills to ensure the treatment is safe and effective for each individual patient using the best available evidence. Developing critical thinking and appraisal skills takes time; however, if you take the time to apply them on a regular basis, your skills will quickly become strong enough to enable you to identify research quality on a spectrum from
high to low quality. This will allow you to determine the “best evidence” available, then apply the findings of the studies (given adequate reporting) within the context of your individual patients when combined with your clinical experience. Thus, critical thinking in rehabilitation research supports evidence-based practice...and gives you another critical skill that's much-needed in our profession: quality peer reviewers.

References


Table 1: The 8 R’s of applying critical thinking to rehabilitation research.

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RESEARCH DESIGN

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RELATIVITY

Compared to other treatments, is this better, worse or same?

REFERENCE

What’s the impact / credibility of the source?
The Prevention and Treatment of Running Injuries: A State of the Art

Christopher Napier, PT, PhD\textsuperscript{1, 2}, Richard W Willy, PT, PhD\textsuperscript{2}

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Keywords: running, injury prevention, treatment, training load, footwear

Despite decades of efforts, running injury prevention programs continue to fall short of achieving a reduction in running injury rates\textsuperscript{1} and most running injuries are notorious for their high recurrence.\textsuperscript{2} Prevention and treatment efforts often focus on a sole factor, such as muscle strengthening or biomechanics, despite the multifactorial nature of running injuries. Additional emphasis on low-value interventions such as footwear to prevent injury often detracts from more effective prevention strategies.\textsuperscript{3} Not surprisingly, most running injury prevention programs fail to reduce running injury rates and, in the case of advising on running biomechanics, may actually increase the risk of running injury.\textsuperscript{1} The purpose of this international perspective is to describe how a causal framework approach can help to prevent and treat running injuries. Causal frameworks provide an important path forward for running injury prevention and treatment efforts by considering how training loads interact with modifiers (i.e., risk factors). Bertelsen et al\textsuperscript{4} introduced a causal framework for the aetiology of running injuries that identified the complex interplay of training load (i.e., number of running steps) with the distribution of biomechanical loading across anatomical structures, magnitude of internal biomechanical loads, and an anatomical structure’s capacity to tolerate the load. For instance, male masters runners have an elevated risk for Achilles tendinopathy due in large part to age-related reductions in Achilles tendon stiffness.\textsuperscript{5} Rapid increases in hill running or speedwork distribute a greater degree of biomechanical loads on the Achilles tendon, potentially resulting in an injurious training load in the masters runner. Importantly, runners who are not at-risk for Achilles tendinopathy, such as adolescent runners, may not experience the same injury under similar training loads. A critical concept in Bertelsen’s causal framework is that a runner’s biomechanics distributes the loads to various structures, but an injury will not result without a training load error coupled with a compromised load capacity of the anatomical structure.

More recently, Kalkhoven et al\textsuperscript{6} provided an important update to the Bertelsen framework by incorporating the tissue-specific microdamage that occurs from biomechanical loading and the ability of the athlete’s underlying physiology to support tissue adaptation. The Kalkhoven framework applies an important concept long-known in tissue mechanics: cumulative biomechanical loads have a non-linear relationship with cumulative tissue damage. For instance, a 10% increase in tissue stress/strain magnitudes results in a 50% reduction in the number of loading cycles (i.e., steps) before tissue failure.\textsuperscript{7} This key, non-linear relationship may explain how a sudden addition of speedwork, for instance, can result in injury even if weekly running volume remains unchanged.\textsuperscript{8} Yet, running injury prevention programs often view added training load as a linear issue, focusing more on training volume than loading magnitude.

Since tissue is not an inert structure, consideration of the ability of the athlete’s physiology to support tissue adaptation in response to loading is a critical component in understanding running injuries. Important physiological concepts, namely Relative Energy Deficiency in Sport (RED-S), have not had enough focus in prevention and treatment programs. The treatment of bone stress injuries in runners is emblematic of the problem of concentrating on an isolated risk factor (e.g., biomechanics) while ignoring other keystone contributors, such as energy availability. If energy availability is insufficient to support bone remodeling, addressing biomechanics or prescribing targeted bone loading exercises will likely have minimal therapeutic effect.\textsuperscript{9}

Adopting a causal framework can greatly inform injury prevention and treatment efforts by tailoring a program to the runner’s risk profile and recent training loads. Enhancing pre-run load capacity of the athlete via consistent, progressive loading (progressive strengthening, minimizing training spikes), addressing psychological stressors, and optimizing a runner’s physiology is the first step. Second, considering the attributes of the individual runner (i.e., masters male vs adolescent female) and the ability of the athlete’s physiology to support tissue remodeling will help inform physiological interventions and training load pre-
scription. Tailoring training load prescription to address structure-specific cumulative microdamage should also be specific to past injuries or anatomical structures that are more likely to experience injury in specific sub-populations. For example, those recovering from, or at-risk for, Achilles tendinopathy should add speedwork into a training program judiciously, whereas downhill running should be added in slowly if recovering from, or at-risk for, patellofemoral pain. Wearable technologies can monitor injury-specific training loads (i.e., number of steps) while performing activities known to increase loading on injury-susceptible tissues, helping inform the need for recovery days to restore pre-run load capacity and support tissue adaptation. Lastly, clinicians should adopt routine screening for RED-S and other physiological conditions known to reduce tissue adaptability and refer out for specialized care when indicated.

We believe that by employing a causal framework of running injury aetiology that considers current theory in tissue mechanics and physiology, and by following general principles of injury risk management, the puzzle of running injury prevention and treatment has potential to be solved.

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Anterior Cruciate Ligament (ACL) injuries are one of the most deleterious knee injuries reported in sport. They continue to confound the sports medicine community, particularly with respect to the high rates reported in girls and women.1–4 There are approximately 200,000 to 250,000 ACL injuries that occur in the United States annually, a rate that has doubled over the last 20 years.5,6 Approximately 25% of these injuries occur in youth athletics; and this rate has been increasing by a rate of 2.5% annually in the United States7 and has increased by 147.8% over a 10 year period in Victoria, Australia.8 Although the overall rate of ACL injury is higher in males, primarily due to greater opportunity(s) to participate in contact sports, the relative risk of ACL injury in women is 3 to 8 times greater than males.9,10 In the National Collegiate Athletic Association (NCAA), the rate of ACL injuries incurred by collegiate females is three times higher compared to men.1 In high school aged athletes (13-18 years), there is approximately 1.6-fold greater rate of ACL tears in females,11 and a multisport female athlete is estimated to have a nearly 10% risk of incurring an ACL injury during her high school or secondary school career.12

A concerted effort has been made over the last three decades to address the complexities of the “sequence of prevention”; to mitigate ACL injury risk by virtue of the implementation of validated injury prevention programs (IPP) interventions.13,14 A vast majority of these IPP’s were designed specifically to address ACL injury in females.15–19 The targeted risk factors included anatomic, environmental, hormonal, genetic and biomechanical.20,21 These neuromuscular IPP training programs, that addressed the biomechanical deficiencies, included in-season elements of strength, plyometrics, sport specific agility drills, proper landing technique, proprioception, proximal control and a biomechanical emphasis on addressing the most common pathokinematic movement patterns associated with ACL injury mechanisms.22–24 Additional components of successful ACL IPPs include socio-economic feasibility, sports-specificity, physiological competency, neurocognitive and psychological (improving confidence and reducing fear) and implementation strategies that may improve overall program adoption.25–28 The IPP’s were typically designed as in-season dynamic warm-up programs, included both intrinsic and extrinsic cues, were strategically offered at no or low-cost, included coaching and athlete web-based educational tools, and were time efficient to promote overall team compliance, program fidelity and adherence.19,29–31 The IPP’s have been largely successful; reporting overall ACL injury reduction rates between 55–88%.16,17,19,31–35 The programs are designed to be introduced during pre-season and continue throughout the season to mitigate biomechanical recidivism.34,35 Additionally, the day in which the IPP was performed resulted in even lower ACL injury rates, suggesting that a transient, neural preparedness and cortical control element may be favorably impacting overall biomechanics and motor control.30,36 Including principals of motor learning theories as a component of rehabilitation and in IPPs has led to improvements in efficiency of the motor cortex, ostensibly allowing the athlete to make improvements to their biomechanics while allowing them to interpret and process rapidly changing environmental stimuli due to improved neurocognitive availability.37,38 Optimization of IPPs must include a synergy of cognitive, perceptual, and motor processes to enhance the athletes’ ability to respond to sport-specific demands with comprehensive and low-risk biomechanical movement strategies.39

Recent studies have retrospectively analyzed injury mechanisms in male and female athletes to further elucidate the biomechanical pathokinematics specifically involved in the mechanism of injury.40–50 Video analysis of ACL injuries in male and female athletes have begun to effectively delineate high risk positioning associated with the injury, namely defensive and unanticipated play, with the injured player demonstrating at or near full hip and knee extension, perturbation to the trunk resulting in lateral trunk displacement, hip adduction and internal rotation, knee valgus, and tibial torsion.40,51,52 Females were more likely to be defending or in an unanticipated/reactive
position and were more likely to tear their non-dominant limb.41,53

Studies analyzing the role of peripheral fatigue and its role in ACL injury have been in consistent.54 A study analyzing female ACL injury mechanisms suggested that fatigue was not correlated with injury, as 64% of injuries occurred in the first 30 minutes of a soccer match.49,55 However, peripheral fatigue has been shown to be a variable for women in Irish Amateur Rugby56, altering biomechanics during landing performance at initial contact57,58, increasing trunk flexion59, and reducing peak knee extensor torque60,61. Inclusion of fatigue as one of the metrics for IPP efficacy should be considered.58 There is inherent complexity to determining the external validity of fatigue on ACL injury incidence. As fatigue increases, psychological stress may increase (stress, emotional lability) and physical response may decrease (performance, velocity, neuromuscular workload and intensity). The decrease in player intensity, performance, and velocity may be more reflective of central fatigue and may ultimately mitigate the overall risk of ACL injury.58 The continued identification and understanding of the intrinsic and extrinsic sex related ACL injury risk factors will increase the clinician’s ability to elucidate and improve IPPs to effectively decrease the ACL injury rate in sport.

One of the major difficulties researchers are enduring, from a public health perspective, is achieving widespread program adoption and implementation of the established and validates IPP’s. Despite the earnest efforts of researchers to mitigate ACL injury rate through the development and the evolution of the aforementioned IPPs, the programs’ potential to reduce risk has been hindered by the overall low adoption rate of these programs. Interestingly, it has been well documented that high compliance to a scientifically vetted IPP can substantially mitigate ACL injury rates.62–67 Conversely, when overall compliance was low and the IPPs were performed less than once per week and/or with low program fidelity, the IPPs were found to be largely ineffective.68,69 Upon analyzing coaching decisions to consistently using an IPP program, researchers determined that it requires a detailed understanding of the unique implementation context, including exercise variety and modification to expand its’ reach, sport specific exercises, incorporating sport specific equipment, time and cost efficacy, greater exercise variations and increased difficulty in program progressions.70,71 These alterations should be heavily considered in IPP design, as the cohesive and consistent implementation of IPPs is a very viable, impactful, and cost-effective option to reducing the overall rate of ACL injury.72 Several studies have demonstrated a positive effect of IPPs on its effectiveness as a warm-up and overall athlete performance.73–76 Optimizing implementation and team compliance, particularly at the youth and recreational levels, lies within the coaching decision making paradigm. The notion of improved performance, recognized by and improved win-loss record, and decreasing overall injury rate to improve player availability may optimally incentivize coaches and players to incorporate an IPP with regularity.77 (Silvers-Granelli, in peer review, Sports Health).

A more nuanced narrative has recently emerged with respect to challenging the prevailing ACL injury prevention debate; are females truly more vulnerable to ACL injury or is this simply a consequence of a series of gendered societal and environmental decisions? Most ACL epidemiological and mechanism studies have been centered around gender-based biology, without considering other social, economic, contextual, and environmental factors. There is a significant disparity in training, coaching and competitive resources in female sports. Despite the advent of the Title IX Educational Amendment in 1972, which prohibited sex discrimination in any education program or activity receiving federal financial assistance in the United States, there is an incongruency in what females are afforded in competitive sporting environments.78 This includes, but is not limited to, decreased overall salaries for coaching and professional play, diminished access to exercise equipment and high quality and consistent rehabilitation, lower standards for coaching, medical staffing and strength and conditioning professional experience, and decreased access to childcare and maternity benefits during their professional careers.79 The impact of ACL injury and reconstruction have also differed in males versus females. Upon a two-year longitudinal analysis, females have demonstrated reticence in return to play activity, exhibited through behavioral self-modulation, by virtue of a decrease in vigorous activity, decreased triple hop distance, and a shift away from team sport participation to mitigate secondary injury risk.80 This concerted decision, to decrease overall secondary risk through behavioral modification, may be partly due to the fact that the risk:reward balance that exists for men is simply not a realistic option for most women. It would behoove the research community to consider additional possibilities to the existing “biological element” influences that currently dominate the prevailing ACL injury prevention algorithm.

As we embark upon our fourth decade on the ACL injury mitigation journey, perhaps we “pivot” and discuss how we effectively disseminate information in a way that encompasses the current social, economic and environmental sex differences across sport. It we recognize the current inequity, and scientifically modify our algorithms, our prevention outreach and interventions may be perceived more favorably and just might increase their overall efficacy. Let us all be prescient as we attempt to minimize the current gender gaps present across sport and respond accordingly.

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Why Female Athletes Injure Their ACL’s More Frequently? What can we do to mitigate their risk?


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Systematic Review/Meta-Analysis

The Systemic Effects of Blood Flow Restriction Training: A Systematic Review

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Background

Blood flow restriction (BFR) training has been reported to have significant benefits on local skeletal muscle including increasing local muscle mass, strength, and endurance while exercising with lower resistance. As a result, patients unable to perform traditional resistance training may benefit from this technique. However, it is unclear what effects BFR may have on other body systems, such as the cardiovascular and pulmonary systems. It is important to explore the systemic effects of BFR training to ensure it is safe for use in physical therapy.

Purpose

The purpose of this study was to systematically review the systemic effects of blood flow restriction training when combined with exercise intervention.

Study Design

Systematic review.

Methods

Three literature searches were performed: June 2019, September 2019, and January 2020; using MedLine, ScienceDirect, PubMed, Cochrane Reviews and CINAHL Complete. Inclusion criteria included: at least one outcome measure addressing a cardiovascular, endocrinological, systemic or proximal musculoskeletal, or psychosocial outcome, use of clinically available blood flow restriction equipment, use of either resistance or aerobic training in combination with BFR, and use of quantitative measures. Exclusion criteria for articles included only measuring local or distal musculoskeletal changes due to BFR training, examining only passive BFR or ischemic preconditioning, articles not originating from a scholarly peer-reviewed journal, CEBM level of evidence less than two, or PEDro score less than four. Articles included in this review were analyzed with the CEBM levels of evidence hierarchy and PEDro scale.

Results

Thirty-five articles were included in the review. PEDro scores ranged between 4 and 8, and had CEBM levels of evidence of 1 and 2. Common systems studied included cardiovascular, musculoskeletal, endocrine, and psychosocial. This review found positive or neutral effects of blood flow restriction training on cardiovascular, endocrinological, musculoskeletal, and psychosocial outcomes.
Conclusions

Although BFR prescription parameters and exercise interventions varied, the majority of included articles reported BFR training to produce favorable or non-detrimental effects to the cardiovascular, endocrine, and musculoskeletal systems. This review also found mixed effects on psychosocial outcomes when using BFR. Additionally, this review found no detrimental outcomes directly attributed to blood flow restriction training on the test subjects or outcomes tested. Thus, BFR training may be an effective intervention for patient populations that are unable to perform traditional exercise training with positive effects other than traditional distal muscle hypertrophy and strength and without significant drawbacks to the individual.

Level of Evidence

INTRODUCTION

Blood flow restriction (BFR) training has been found to have significant benefits for skeletal muscle development. BFR uses a belt or tourniquet applied to the proximal portion of an extremity to partially or fully occlude blood flow in order to stimulate muscular adaptations that improve muscular mass and strength. Traditionally, when attempting to improve muscle mass and strength, high intensity resistance training, cardiovascular endurance training, and other forms of exercise not generally indicated to improve muscular mass/strength also cause these muscular adaptations.

These findings may make the use of BFR valuable in the rehabilitation of patients who may not be able to perform high load resistance training such as the elderly, patients undergoing rehabilitation, recovering athletes, or in patients with other medical conditions such as renal disease, metabolic dysfunction, heart disease, or medically compromised risk patients. Findings also suggest that those using BFR during training such as a cycling exercise program may receive the benefits of increased skeletal muscle mass and strength along with improved cardiovascular/muscular endurance.

Typically, research on BFR training reports the localized changes in muscle mass, strength, and muscle endurance of the extremity on which the cuff is applied. Research on BFR training has suggested other possible benefits or detriments involving systems other than the musculoskeletal system; however, these effects have not been determined conclusively. The focus of BFR is to cause beneficial adaptations to local skeletal muscle, but there is limited information reported on the effects of BFR training on other body systems. Multiple systems may be affected by BFR training, but a thorough analysis of these effects is still needed.

In order to better understand BFR and its overall impact on the human body, the purpose of this study was to systematically review the systemic effects of blood flow restriction training when combined with an exercise intervention. By further understanding the systemic effects of BFR training, clinicians may be able to incorporate this technique safely in the rehabilitation of patients who cannot perform high load resistance or aerobic training.

METHODS

An original database search was completed in June 2019 with a focus on the topic of the systemic effects of blood flow restriction (BFR) training. The following databases were used in the search: MedLine, ScienceDirect, PubMed, Cochrane Reviews and CINAHL Complete. Initial search terms included "blood flow restriction", "occlusion training", "restriction of blood flow", "systemic effects", "blood flow restriction training", "partial occlusion", "effect or effects". Search criteria were filtered by article type (research articles, practice guidelines) and the year range 2009-2020. Titles and abstracts of articles were assessed by one of the four authors and a hand search of the systematic reviews by four authors yielded additional articles that were deemed relevant based on their titles and abstracts. Exclusion criteria for articles included research focusing on local musculoskeletal changes due to BFR training, studies examining passive BFR or ischemic preconditioning, and articles that did not originate from a scholarly peer-reviewed journal. Studies with CEBM level of evidence less than two were excluded, as the focus of this article was to review meta-analyses, RCTs, and cohort studies. Additionally, studies with PEDro scores less than 4 were excluded, as this score has been used previously to delineate "poor" quality from "fair", "good", and "excellent" quality studies. Four researchers calculated PEDro scores and CEBM levels of evidence and came to mutual agreement regarding when articles should be excluded due to inadequate quality. Articles were included if researchers used clinically available blood flow restriction equipment, used resistance or aerobic training in combination with BFR, used quantitative outcome measures, and were not dismissed by the exclusion criteria.

Updated database searches were completed in September 2019 and January 2020. These articles were screened using their titles and abstracts for relevance, inclusion, and exclusion criteria, as well as Oxford Centre of Evidence-Based Medicine level of evidence by one of four researchers. If deemed appropriate, the author evaluated the entire text for quality using the PEDro scale. If the article was a systematic review a hand search of references was performed, and results were assessed.

After the June 2019, September 2019, and January 2020 searches were completed, Inter-library loans through Misericordia University and ResearchGate requests were completed for articles that were unable to be accessed through
the original databases. Any articles not received or granted access by February 1, 2020 were not included in the review due to a lack of access.

RESULTS

The initial search completed in June 2019 produced 2299 results. After refining parameters and removing duplicates, 281 articles were considered appropriate. Upon assessment of the abstracts and titles of all 281 articles, 30 articles and three systematic reviews were deemed appropriate for use in this review. After hand searching the systematic reviews, 41 additional articles were found and determined to be suitable. The updated search in September 2019 yielded 86 results, of which five articles were deemed appropriate. The updated search in January 2020 yielded 98 results, and six articles and one systematic review were determined to be suitable. Upon hand search of the systematic review, eight additional articles were located and considered to be appropriate. Ninety total articles were reviewed, and after 55 were excluded due to either lack of relevance, quality, or access, a total of 35 articles were included in the systematic review. Appendix 1 summarizes the characteristics and results of studies included in this review. Figure 1 describes the search timeline and methodology.

CARDIOPULMONARY

A paramount concern regarding the application of the BFR training is the effects partial vascular occlusion has on cardiovascular and pulmonary health. The search found articles investigating the effects on maximal oxygen consumption (VO2 Max),7–11 vascular stiffness and compliance,5,12–19 systolic and diastolic blood pressure (SBP and DBP, respectively) responses,5,16–23 heart rate (HR),7,16–19,24 stroke volume (SV),17,18 cardiac output (CO),17,18 ankle brachial pressure index (ABI),3,19 and functional endurance in healthy adults9 and those with renal disease25 and heart failure.26

BLOOD PRESSURE

Five studies examined the effects of BFR on systolic and diastolic blood pressure responses.5,16–25 In young adults using BFR during resistance training for hypertrophy it appears the modality causes no differences in SBP or DBP responses both during and after exercise when using between 50–80% aortic occlusion pressure at the proximal thighs or proximal upper arms and less than 20% 1-RM.3,22 In a group of young men performing six week bench press training with either proximal arm BFR at pressures of 160 mmHg and 50% 1-RM (BFR group) or no occlusion and 75% 1-RM (HIT group), Ozaki and colleagues found thigh SBP increased significantly in the HIT group compared to the BFR group, while both groups’ resting SBP and DBP remained unchanged throughout the intervention period.16

In young adults performing BFR and aerobic exercise with occlusion pressures between 40–60 mmHg and 50% maximum heart rate (HR Max), SBP and DBP responses were found to be similar to those traditionally found with aerobic intensities of 62–85% HR max. With appropriate individualized dosing, aerobic exercise with BFR could provide an appropriate stimulus for aerobic adaptation. Two studies using a 15-minute treadmill test with bilateral lower extremity 160 mmHg occlusion found central SBP and DBP responses were significantly greater than those seen in non-occluded treadmill testing.17,18

In older adults one study found that occlusion pressures of 196 mmHg (+/-18 mmHg) resulted in no differences in SBP and DBP responses between two cohorts of older adults performing upper extremity exercises with or without BFR.19

HEART RATE, STROKE VOLUME, AND CARDIAC OUTPUT

Six articles examined the effects of BFR on heart rate responses or cardiac output.7,8,16,18,19,24 The majority of studies evaluating heart rate (HR) found higher HR responses compared to intensity matched controls with both strengthening and aerobic based exercise.7,16–18,24 One study by Yasuda, Fukushima, and Yuusuke reported no significant differences in the HR responses of two groups of older adults performing elastic band resistance training with or without BFR, when compared to pre-intervention.19 Two studies found smaller increases in stroke volume (SV) while performing aerobic treadmill sessions for BFR groups using 160 mmHg bilateral lower extremity occlusion compared to controls. These studies also evaluated cardiac output (CO) and found both groups increased CO similarly in response to treadmill exercise.17,18

VASCULAR STIFFNESS AND COMPLIANCE

Nine articles evaluated the effects of BFR on vascular compliance or endothelial function.5,12–19 Ozaki et al. reported arterial stiffness increased more prominently in BFR compared to control when using 50–80% AOP.16 Other studies found no difference in arterial responses to exercise when comparing BFR to controls via brachial artery diameter, ankle-brachial index, flow-mediated dilation, and cardio-ankle vascular index.3,19 Ozaki et al. in 2013 found carotid arterial compliance was maintained in their BFR cohort using 160 mmHg bilateral proximal upper arm occlusion during bench press training, compared to a 21% decrease in carotid compliance in controls.15 Ozaki et al. in 2011 found occlusion pressures up to 200 mmHg applied during walk training to bilateral proximal thighs resulted in similar increases in carotid artery compliance compared to traditional walk training.15 Shimizu et al. reported BFR using femoral SBP increased transcutaneous oxygen pressure of the foot compared to both control and pre-intervention levels.14

VO2 PEAK AND VO2 MAX

Six articles in this review assessed the effects of BFR on VO2 peak and/or VO2 max.4,7–11 Two studies evaluating VO2 peak found concurrent resistance training and aerobic exercise or treadmill exercise resulted in similar increases or no change when using occlusion pressures of 50% AOP or 110–200 mmHg, respectively.8,9 Three studies evaluating the impact of BFR with aerobic exercise on VO2 max and found mixed results. Held and colleagues found an average...
improvement of 9.6% in VO$_2$ max of elite rowers when using elastic wrapped BFR during low intensity row training, significantly more than exercising controls.\textsuperscript{10} Oliveira et al. used 18 cm wide cuffs at 140-200 mmHg pressure and found similar increases in VO$_2$ max with 29.4% of the high intensity training group volume.\textsuperscript{4} Paton, Addis, and Taylor found similar increases in VO$_2$ max between BFR and control with the same exercise intensity (running speed as a percentage of peak running velocity).\textsuperscript{7} Mendonca et al. evaluated excess post-exercise oxygen consumption (EPOC) using 200 mmHg occlusion pressure with a 6 cm wide cuff and found walking with BFR increased EPOC post-intervention significantly more than walking without the modality.\textsuperscript{11}

**EXERCISE CAPACITY**

Three articles evaluated exercise capacity: one of healthy adults,\textsuperscript{9} one in patients with end stage renal disease (ESRD),\textsuperscript{25} and one in patients with heart failure (HF).\textsuperscript{26}

In healthy older adults, it appears BFR in combination with six weeks of treadmill walking can improve functional ability as evaluated by Timed-Up-and-Go and 30 Second Sit-to-Stand scores significantly more than walking alone.\textsuperscript{9} In two of the most clinically relevant cardiovascular studies, BFR was found to improve 6-minute walk test distances 17% (compared to 1.5% improvement in exercising control) in patients with ESRD on hemodialysis.\textsuperscript{25} These patients used cycle ergometry and 50% AOP while receiving dialysis treatment. The exercise was performed for 20 minutes of the four-hour dialysis session three times per week, and the researchers reported no adverse effects correlated to the use of the modality. In patients with post-infarction HF with an average ejection fraction of 52.9%, BFR at an average 208 mmHg to bilateral proximal thighs with cycle ergometry was found to significantly improve VO$_2$/W and anaerobic threshold compared to exercise matched controls.\textsuperscript{26}

**SYSTEMIC MUSCULOSKELETAL**

Along with a large array of systemic cardiopulmonary effects, BFR training has also demonstrated a variety of systemic effects on the musculoskeletal system.\textsuperscript{16,27–32} Previous research on the technique has focused on localized muscle hypertrophy, strength, and endurance following application and methodization of BFR training.\textsuperscript{27,28} A vast majority of previous research compares the results of low-
intensity BFR training to high intensity resistance training without BFR in order to determine if low-intensity BFR may be a comparable training stimulus. Although not all the articles were conclusive of definite systemic musculoskeletal effects, many of the studies did report systemic effects involving the musculoskeletal system that were attributed to BFR. When compared to various other training methods or techniques, many of the findings demonstrated noteworthy, or at least comparable, results to other groups. Interestingly, six of the seven articles included in the musculoskeletal portion of the review reported distal or contralateral strengthening, 16,27–31 hypertrophy, 16,27,29–32 or muscle function adaptation 16,27–32 that can be attributed to systemic effects of BFR training.

ENDOCRINE

MUSCULAR ADAPTATION

Cook found that when comparing two groups of young men performing identical exercise programs, one group using BFR and a control group, participants training with BFR see a significantly greater increase in free testosterone concentrations compared to the control. 28

Another important factor in developing muscle, serum growth hormone (GH) concentration was also found to have increased significantly more in elderly participants using BFR training techniques as compared to a non-BFR control group when performing identical low intensity resistance programs. 14

Laurentino discovered BFR may induce muscular adaptations by inhibiting factors that are detrimental to muscle growth. 33 Following 8 weeks of low intensity resistance training with BFR, myostatin (MSTN) mRNA gene expression was found to have significantly decreased (45% decrease in BFR low intensity groups, 41% in non-BFR high intensity group), while Growth and Differentiation- Associated Serum Protein-1 (GASP-1) and MAD-related protein (SMAD-7) gene expressions significantly increased (GASP-1: 82% increase in BFR groups compared to 79% in non-BFR, SMAD-7: 88% increase in BFR group compared to 66% in non-BFR group). 33

In a research study using a sample of healthy elderly men, Karabulut reported no significant change in interleukin 6 (IL-6), insulin-like growth factor-1 (IGF-1), and free testosterone between participants in high-intensity resistance training, low intensity resistance training with BFR, and control groups. 34

OSTEOBLASTIC ACTIVITY

Karabulut et al.’s study investigated BFR’s influence on bone alkaline phosphate (ALP) and C-telopeptide of Type-1 collagen (CTX) as well as ALP/CTX ratio. 35 In 6 weeks, participants performing low intensity resistance training with BFR/vascular restriction (LI-VRT) and high-intensity resistance training only (HI-RT) demonstrated significant increases in ALP concentration and improved bone ALP/CTX ratio as compared to a control group. 35 LI-VRT and HI-RT saw 21% and 25% increases in concentrations, respectively, while the control had an 4.7% increase. LI-VRT and HI-RT saw decreases in CTX concentrations of 7.7% and 4.1%, respectively, while the control group had a 3.3% increase in CTX concentration.

METABOLIC STRESS

Multiple studies have found that when using BFR in conjunction with low resistance exercise, blood lactate levels are significantly higher than control groups and levels are similar to that produced by high intensity training. 4,36 Oliveira et al., found significant increases in blood lactate accumulation (measured before and after treatment) between participants performing low intensity exercises with BFR (16% +/- 15%) and those performing low intensity exercise without BFR (6% +/- 4%). 4 Neto found that groups participating in low intensity exercises with BFR (5.0% increase) provide similar levels of blood lactate accumulation as compared to high intensity exercises without BFR (5.2% increase). 36 Shimizu et al. found when comparing BFR groups to non-BFR, participants using BFR have significant increases in lactate levels (non-BFR: 10.3 +/- 5.3 before, 34.5 +/- 13.5 after; BFR: 8.2 +/- 3.6 before, 49.2 +/- 16.1 after, mg dL^-1) as well as increases norepinephrine (non-BFR: 472.4 +/- 136.8 before, 662.1 +/- 201.5 after; 619.5 +/- 245.7, 960.2 +/- 373.7 after, mg dL^-1).

Okita et al research finds that metabolic stress is induced by decreases in phosphocreatine and intramuscular pH. Participants performing low intensity exercises do not have significant decrease in intramuscular pH while participants using intermittent BFR (-.10 pH) and continuous BFR (-.125 pH) have significant decrease in pH.

HIGH RISK PATIENTS

Tanaka and Takarade’s research investigated the effects of BFR with a patient population of 30 men (mean age of 60.7 +/- 11 years) with a history of CHF. Results after six months of exercise training showed no change in the serum triglyceride, high-density lipoprotein, LDL-C, total cholesterol, glucose, and HbA1c levels. 26 Additionally, after the six-month time frame, brain natriuretic peptide levels decreased significantly. 26

PSYCHOSOCIAL FACTORS

The effects of BFR are not only that of a physical nature, but that of a patient’s psychological state. Furthermore, not only may the effects of BFR impact a patient’s psychological state, but may also affect a patient’s physical state/performance.

To assess these effects multiple studies have assessed an individual’s rate of perceived exertion (RPE), 19,36,37 overall mood, 38,39 pain levels, 37 and overall levels of discomfort. 40

When investigating effects on RPE, studies have found when initially training with BFR and low load resistance training RPE was increased in most individuals as compared to traditional high load resistance exercise. 19,36,37 While RPE initially did increase in most cases during the beginning stages of BFR, RPE rates decreased over a longer period of time lasting 8 weeks when compared to the traditional high load resistance training. 40 When comparing the effects...
of RPE between continuous vs intermittent BFR, the average RPE levels were lower when using intermittent BFR as compared to using continuous BFR.\(^56\)

To evaluate general pain level and level of discomfort, a 0-10 general pain scale and a BORG discomfort scale was used to track these complaints over the BFR application period. In a study using bilateral leg press, both high and low load resistance training using 80% and 30% 1 RM showed higher RPE and pain ratings after exercise to muscular failure than a BFR group training with 30% 1 RM and using 4 sets of 15 repetitions scheme.\(^57\) In a separate study comparing groups performing upper extremity exercises, those participants performing the same exercises with BFR reported significant increases in discomfort rating.\(^40\)

The utilization of BFR with resistance training has been found to have a significant effect on an individuals' overall mood state. Silva 2018 measured mood state, total mood disturbance, and RPE before and after exercising with and without BFR.\(^58\) These researchers found that BFR induced an acute negative effect on mood state, total mood disturbance, and increased overall participant fatigue.\(^58\) Silva 2019 research investigated mood state after aerobic exercise with BFR and found BFR to cause acute impairments in mood state and RPE in most individuals.\(^59\) However, this effect was comparable to the effects found with traditional high load resistance training.\(^59\)

**DISCUSSION**

**CARDIOPULMONARY**

**BLOOD PRESSURE**

Previous studies have shown a correlation between resistance training and training-induced arterial stiffening, and a low level of arterial compliance has been shown to contribute to heart disease and impaired baroreflex sensitivity.\(^20,21,23\) The studies included in this review suggest BFR using occlusion pressures less than approximately 200 mmHg does not lead to detrimental blood pressure responses in healthy adults. Rather, BFR under these parameters causes similar blood pressure responses as traditional exercise, when prescribed appropriately.

**HEART RATE, STROKE VOLUME, AND CARDIAC OUTPUT**

When evaluated together, these studies show the application of BFR does not change CO but does decrease relative SV amount and increase HR response accordingly to maintain appropriate CO. These findings suggest the increased pressure from the occlusion cuffs, when using pressures of less than 160 mmHg or 7/10 subject perceived pressure with resistance or aerobic exercise, does not negatively impact cardiac output. Additionally, the exaggerated HR response may be beneficial for improving cardiac conditioning in those who cannot handle traditional stimuli needed to attain 70-85% HR Max.\(^41\)

**VASCULAR STIFFNESS AND COMPLIANCE**

When using BFR with aerobic exercise, Renzi et al. found increased arterial stiffness (measured using SV/PP) and decreased flow-mediated dilation when using 160 mmHg with walk training.\(^16\) Iida, Nakjima, and Abe found a six week walking program with 140-200 mmHg bilateral lower extremity BFR significantly increased maximal venous outflow and venous compliance compared to no change in their control.\(^15\) Ozaki et al. in the year 2011 found walk training with 140-200 mmHg occlusion pressure did not lead to significantly different changes in carotid artery compliance compared to control.\(^15\) This finding is significant because these authors also found a significant increase in thigh muscle cross sectional area, knee flexion torque, and knee extension torque in the BFR group compared to control. While this finding is outside the scope of this literature review, the possibility of improving muscle hypertrophy and carotid artery compliance concurrently using BFR with aerobic training is worth future investigation.\(^13\)

BFR effects on vascular compliance and stiffness varied among studies.\(^13,14,16-18\) However, it is important to identify the trend of these results: higher relative pressures tend to decrease the benefit and may incur unfavorable changes to the vascular system. A possible explanation of the negative outcomes seen with vascular changes may be explained by the pressure gradient created by narrow width occlusion cuffs. Studies of surgical tourniquets have found an inverse relationship between the width of occlusion cuffs and the pressure required to attain total limb occlusion with a cuff width to limb circumference ratio less than 0.5 requiring sub-systolic pressures.\(^42,43\) In BFR training a similar concept may be paramount to elicit favorable adaptations using the lowest pressures and lowest pressure gradients possible.

**VO₂ PEAK AND VO₂ MAX**

These studies show while benefits to VO₂ peak may not be attainable, VO₂ max can be significantly improved given an appropriate occlusion pressure and training stimulus. Importantly it appears VO₂ max can be improved to a similar degree as traditional aerobic exercise, and this benefit can be realized with significantly less volume when augmented with BFR. Additionally, because BFR seems to increase the relative intensity and cumulative oxygen deficit of an aerobic activity, lower stimuli may be sufficient to incur benefits to VO₂ max.\(^11\) This may be especially valuable to those who are unable to exercise at intensities high enough to improve or maintain aerobic capacity.

**EXERCISE CAPACITY**

These studies are novel in their use of medically complex patients and display how appropriately dosed BFR training with aerobic exercise can safely and significantly improve functional capacity.

In healthy older adults Abe and colleagues found no improvement in aerobic capacity following six weeks of treadmill walking with BFR, however the BFR group did significantly improve chair stand and Timed-Up-and-Go performance compared to an active control. Importantly, the authors did not reach the 50% HR Max reserve intensity they hypothesized was required to elicit aerobic changes, and previous research included in their study concluded "similarly intense walk training without BFR elicits little or
no effect on aerobic capacity.9
Cardoso and colleagues noted the improvement realized in their study could be due in part to the higher metabolic stress generated by hypoxia from BFR, a hypothesis that has been put forth to explain strength and hypertrophy gains experienced with this modality.

When using BFR with post-infarction heart failure patients, Tanaka and others found significant improvements in anaerobic threshold using BFR with cycle ergometry. This study is significant in its use of high occlusion pressures (208.7+/− 7.4 mmHg) with exercise in medically complex patients with no adverse effects of exercise training noted.26 While a small study, the significant improvement in anaerobic threshold compared to exercising control without adverse training effects is encouraging for the safe use of this intervention in this population and others with cardiovascular conditions.

SYSTEMIC MUSCULOSKELETAL

STRENGTH

Several studies have determined that low-load BFR training may increase strength contralateral and distal to cuff or tourniquet placement.16,27–31 Compared to high-load resistance training, low-load with BFR has shown to produce similar, and sometimes more significant, effects on muscle strength.27 Cook et al. discovered a systemic effect of increased muscle strength of the upper extremities when occluding bilateral lower extremity blood flow.28 BFR training with similar exercise regimen as the control group demonstrated a significantly greater increase in bench press strength compared to the non-BFR group, 1.4% ± 0.8%.28 Occlusion of lower extremities increasing upper-body strength more than a group without BFR validates the idea that there is a systemic effects on the body, but the overall mechanism of these effects are yet to be fully understood.28

May et al. used lower extremity BFR training following unilateral arm exercises and during lower extremity exercises to demonstrate a larger increase in trained arm strength of the BFR group compared to the trained arm of the control group, which displays a possible systemic effect stemming from partial blood flow occlusion. The systemic or “transfer effect” on upper body strength is supported by the increased elbow flexion 1-RM in the untrained arm of the experimental group.29 May et al.29 and Cook et al.28 hypothesized that noted systemic musculoskeletal effects of BFR can be attributed to what has been called the “cross-transfer phenomenon”. According to May et al., cross-transfer is common with unilateral resistance training, with contralateral sites. However, there has not been much research on isolated sites and their effect on other sites; it is believed in this study BFR of the lower extremities had a cross-transfer effect on the upper extremities. May et al. also suggests that because cross-sectional area of musculature grew similarly between extremities, the strength transfer was not due to hypertrophy of muscle, but rather a neuromuscular adaptation.29

Bowman et al. also found contralateral lower extremity strength gains in the low-load BFR group compared to low-load training alone.27 The control group performed low-load resistance training of the lower extremities, whereas the BFR group performed the same exercises but with partial occlusion to blood flow of the upper thigh of one lower extremity.27 Bowman hypothesizes that improved strength and increases in muscle hypertrophy are due to metabolic stress triggering consequent metabolic, adrenergic, and hormonal changes that eventually lead to muscular adaptation.27 Both Ozaki et al.16 and Thiebaud et al.30 discovered similar effects on strength gains between BFR and non-BFR groups. Ozaki et al. found that when occluding upper extremity blood flow, the BFR group produced similar gains in bench press 1-RM compared to the non-BFR group, but the BFR group was working at 45% lower intensity.16 Thiebaud et al. found that BFR with cuffs placed on upper extremities demonstrated significant increases in strength of chest press, shoulder press, and seated row equal to the non-BFR group with no significant differences between the two.30 Again, the BFR group was exercising at a lower intensity, but still demonstrated equal gains in strength.

Yasuda et al. found that when the training intensities remain the same, and the only difference between two groups is BFR of the upper extremities, the BFR group demonstrated more significant changes in bench press 1-RM compared to the non-BFR group. Because they also found increases in muscle hypertrophy, Yasuda et al. believes strength gains cannot be due to neural adaptation alone.31

HYPERTROPHY

Both Thiebaud et al.30 and Ozaki et al.16 compared moderate to high intensity resistance training to low intensity resistance training with BFR and their effect on, cross-sectional area (CSA) of pectoralis major when occluding blood of the upper extremities. Findings of the studies determined that even with a lower workload, the BFR group experienced almost equivalent pectoralis muscle hypertrophy as their counterpart.16,30 Thiebaud et al. also found that there were no significant differences between groups concerning lower extremity muscle hypertrophy, but both groups experienced significant changes in upper thigh muscle thickness with the BFR group exercising at a lower intensity.30 With unilateral LE occlusion, Bowman et al. found greater increase in contralateral BFR lower extremity compared to non BFR group.27 May et al. found that, with similar exercise regimens, BFR applied to the most proximal portion of bilateral lower extremities did not promote a significantly different change in upper extremity muscle hypertrophy compared to the non-BFR group.29 Because there was strength gain without an increase in muscle size, it is clear why May attributes the systemic increase in strength attained from BFR to neuromuscular adaptation and not to musculature hypertrophy.29 This finding is in contrast to previous findings from Yasuda et al. who reported a measurable increase in muscle size. Yasuda et al. determined that, with identical resistance training protocol, bilateral upper extremity BFR promotes significant increase in unrestricted chest muscle hypertrophy (pectoralis major) compared to no BFR.31Unlike multiple previous studies, Sakamaki et al. compared a BFR exercise group to a non-BFR exercise group and determined no or minimal difference in systemic muscle hypertrophy of gluteus maximus and iliopsoas muscles between
the groups. The BFR cuffs were placed around the most proximal portion of each leg, and the regimen consisted of three weeks of treadmill walking training. Their findings may be due to the fact that the training regimen was not as intense as resistance training exercises, making it less likely muscles would hypertrophy.

ENDOCRINE

Multiple studies have demonstrated that BFR has a profound effect on the endocrine system by affecting the hormones, blood factors, and biological complexes which control the human body. These changes might not only impact muscle, but also multiple body systems. Knowing the endocrinological changes induced by BFR is not only important to understand how BFR is an effective tool, but if/how it can be a danger to potential patients.

MUSCULAR ADAPTATION

BFR's greatest potential as a therapeutic tool comes from its ability to improve muscle strength and induce muscle hypertrophy without placing the physical stress of high intensity resistance training on the body. These muscular adaptations may come as a result of the hormonal changes BFR induces.

Increases in free testosterone as well as serum growth hormone may be one of the mechanisms in which BFR helps induce muscular adaptation. Increases in these hormones promote the growth of muscle tissue allowing for potentially greater increases in strength as compared to changes induced by low intensity exercise only. Laurentino et al. suggest that BFR promotes increased muscle growth through its effects on Myostatin (MSTN), Growth and Differentiation- Associated Serum Protein-1 (GASP-1) and MAD-related protein (SMAD-7) gene expressions. MSTN plays a role in controlling/inhibiting muscle growth, while GASP-1 and SMAD-7 play roles in inhibiting MSTN formation/function. As a result, the increases in GASP-1 and SMAD-7 expression will decrease the inhibitor actions of MSTN, and the decrease in MSTN expression means overall less active inhibition of muscle growth.

Karabulut's findings leave questions unanswered regarding the mechanism by which BFR may demand muscular adaptation. Finding that there was no significant change in growth factors/hormones, such as IL-6, IGF-1 and free testosterone, that would promote muscle growth may mean that it is not hormonal effects that cause muscular adaptation.

OSTEOBLASTIC ACTIVITY

An important benefit of resistance training, especially in the elderly, is its ability to increase bone density/mass. Increasing bone density and mass is important in order to prepare for degeneration with natural aging and prevents injury in the future. The results of Karabulut et al.'s research found that both treatment groups (low intensity resistance training with and without BFR) will benefit from a shift in bone turnover/metabolism that favors bone formation. However, this positive shift in osteoblastic activity shows that BFR in conjunction with low intensity exercise can facilitate improvements in bone density without placing the body through the physical stress of high intensity resistance training.

METABOLIC STRESS

One of the most significant endocrinological changes that is induced by BFR training is increased blood lactate levels. Studies have found that when using BFR in conjunction with low resistance exercise, blood lactate levels are significantly higher than control groups and levels are similar to that produced by high intensity training. Increased lactate levels lead to increased muscle soreness and fatigue, which might discourage participants from continuing the training practice/therapy service. However, it would seem that this increase in lactate levels is an important mechanism for beneficial muscular adaptations as one theory behind BFR’s effectiveness suggests that the low oxygen environment promotes high metabolic stress (by high lactate levels). This increased metabolic stress causes the process of muscle damage and repair, which leads to muscle growth. Not only is it speculated that increases in lactate levels cause metabolic stress which induces muscular adaptation, but Okita finds that decreases in intramuscular PCR and intramuscular pH cause equivalent stress (with moderate resistance). Their studies suggest that these changes induce stress and drive muscular adaptation, similar to the effect of lactate.

Shimizu et al. conducted studies to identify the impact of BFR on endothelial function and peripheral circulation in the elderly while also looking at blood lactate levels (source of metabolic stress). The authors surmise that the increases in norepinephrine are needed in order to increase HR and BP to levels that allow sustainable, safe exercise while using BFR techniques, which induces significant metabolic stress. However, more research is needed to investigate if lactic acid and pH have the potential to reach levels in which the participant enters metabolic acidosis. Additionally, specific research is needed to evaluate risk of metabolic acidosis during BFR training in patients with diseases such as kidney failure. This need for further research should be expanded to investigate how the physical and metabolic stresses of BFR techniques affect a multitude of conditions.

HIGH RISK PATIENTS

To utilize BFR’s potential, research needs to confirm that BFR may be used safely with patients that are medically compromised/high-risk. Tanaka and Takarade’s research specifically investigated the effects of BFR on patients with CHF. Overall, their research finds that in a population of men (mean age of 60.7 +/- 11 years) there were no noticeable adverse effects of BFR training in conjunction with aerobic exercise. Even though a goal of exercise is to improve cholesterol and glucose levels, a lack of change in these levels and no described adverse effects shows that the stress of BFR can be properly tolerated by elderly patients with CHF under proper guidance. However, there are significant limitations to this study as effects were not investigated for women of any age, men of younger age, and those
with other significant diagnoses.

**PSYCHOSOCIAL FACTORS**

As discussed earlier, BFR does not only have physical effects but appears to have psychological effects as well. This psychological effect may deter an individual from participating in BFR training and may, furthermore, cause a negative impact to one's physical performance/state.

Increases in RPE may initially deter individuals as they are reporting feelings of having to exert more effort as compared to traditional training.\(^{19,36,37}\) This may be especially true in the field of physical therapy as we see many individuals that do not normally participate in strength training or may have individuals that are already poorly motivated to participate in physical activity. However, this review also shows RPE may initially be significantly higher, but with continued training, it appears most individuals build tolerance to the practice and RPE levels decrease when compared to traditional training.\(^{40}\) To potentially minimized the negative impact of elevated RPE, intermittent BFR may be more tolerable compared to continuous BFR as it is found to produce lower reports RPE over a training session.\(^{36}\)

When looking at discomfort and pain ratings with BFR there is less definable changes. When comparing participants performing LE exercises, researchers suggest that those using BFR in conjunction with low intensity resistance training may have similar physical effects to those performing higher intensity exercise without BFR while participants using BFR complained of less pain over time.\(^{37}\) However, when measuring discomfort in participants performing upper UE exercise, BFR groups were found to have higher complaints of discomfort compared to their non-BFR counterparts.\(^{40}\) Further research will need to be conducted due to the different variables between these studies, but it appears that from this data, overall pain ratings decrease overtime with use of BFR while overall discomfort rating increased overtime.

Due to the negative effects to overall mood state and total mood disturbance, it is suggested that BFR is not to be used directly prior to athletic competitions.\(^{38}\) Decreased mood and the described participant fatigue caused by BFR may leave an athlete at a disadvantage compared to those that feel rested and prepared for competition.

While BFR has been found to have many positive physiological effects, it is important to consider the potential effects that it can have on the mood and psychological state. The benefits of a decreased RPE over time and negative effects on acute mood state need to be compared for each individual in order to determine whether this intervention is beneficial for them.

**LIMITATIONS**

While completing this research, several limitations were identified that could potentially affect the significance of the findings. While all studies were utilizing blood flow restriction techniques in combination with exercise, the application and dosing parameters were widespread and not standardized between studies. It is unclear whether the results of each study would be significantly changed with different application and dosing parameters, which poses a limitation to this review. In addition to the non-standardization seen in dosing parameters, the studies utilized in this review did not provide diverse patient demographics. Most studies utilized a patient population between the age range of 18-39, offering little information on the older adult population. Similarly, the studies did not commonly include disease-specific populations, as most of the studies were performed on healthy individuals. This poses a limitation to the generalizability of this findings as they are limited to a mainly younger, healthy population. Finally, a potential conflict of interest is present due to several articles used in this review being authored or contributed to by Dr. Yoshiaki Sato, who is credited with inventing KAATSU training, a form of BFR, and holds several patents on BFR products. Studies coauthored by individuals related to this organization have been noted in Appendix 1. As these researchers may be invested in seeing beneficial impacts of this technique, their findings should be scrutinized.

**CONCLUSION**

The results of this systematic review suggest that blood flow restriction training has wide reaching effects on multiple body systems including cardiopulmonary, vascular, systemic musculoskeletal, and endocrine, as well as psychosocial factors. Overall, it does appear that BFR is beneficial to patients performing this style of training with currently no known adverse effects when dosed properly. In studies performed using patients with heart and renal disease, the use of BFR was not detrimental and even induced some benefits. It appears the greatest advantage of BFR is its ability to safely augment exercise intensity in both healthy and comorbid individuals. However, more research is needed before fully determining the long-term systemic effects of BFR. Further research is needed to investigate the appropriate dosing parameters, including ideal cuff width, pressure, and duration of partial occlusion. Once a "gold standard" BFR protocol is developed, the research of this review should be replicated to evaluate the reliability of the data.

**COI STATEMENT**

The authors of this systematic review report no conflicts of interest, financial or otherwise, in the production of this manuscript.

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REFERENCES


SUPPLEMENTARY MATERIALS

Appendix 1

Background

Mobile electronic devices have become integral tools in addressing the need for portable assessment of cognitive function following neurocognitive/motor injury. SWAY Medical, Inc., has employed mobile device motion-based technology in the SWAY Cognitive Assessment (SWAY CA) application to assess cognitive function.

Purpose

The purpose of this study was to assess whether the SWAY CA application (reaction time, impulse control and inspection time) was able to reliably operate on different mobile devices and operating systems (iOS, Android). The study further sought to assess the validity of the SWAY CA application against the FDA approved ImPACT QT mobile device application.

Study Design

Original Research, observational study of validity.

Methods

88 healthy, young adults, 18 to 48 years (mean = 22.09 ± sd=4.47 years) completed four, randomized and counter-balanced, reaction time tests (2- SWAY RT, 2- ImPACT QT) using different operating systems (iOS, Android) of 4 randomly assigned mobile devices.

Results

ANOVAs reported the SWAY CA application (reaction time, impulse control, inspection time) operated reliably with iPhone 6S, Samsung Galaxy S9, and iPad Pro 5 mobile devices (p > 0.05), respectively. Google Pixel 3 reliability with SWAY CA application remains undetermined. SWAY CA simple reaction motion measures were in agreement (r = -0.46 to 0.22, p ≤ 0.05) with several ImPACT QT reaction time measures. SWAY CA impulse control and inspection time measures are weakly correlated (r = -0.25 to -0.46, p ≤ 0.05) with five ImPACT QT reaction time measures.

Conclusion

The motion-based SWAY CA mobile device application appears to reliably operate when being administered on different mobile devices and software operating systems. Furthermore, the SWAY CA application appears to be comparable to the ImPACT QT and serve as a valid tool for assessing reaction time measures.
Level of Evidence
Level 2b (observational study of validity).

INTRODUCTION

Reaction time is known as an individual's rate of response (or amount of time lapsed) following the introduction of a known or unknown stimulus.\textsuperscript{1} It is an important indicator of one's neurocognitive and functional health,\textsuperscript{1–3} as well as being a key factor in many daily activities such as participating in sport, driving a car, and even in emergency situations.\textsuperscript{3} The assessment of reaction time has long been used to evaluate an individual's cognitive, neurological, and motor (dys)function,\textsuperscript{4} and more recently has become a respected measure for return-to-play in sport(s) following mild-traumatic brain injury (MTBI).\textsuperscript{5,5,6} For example, immediately following a sport-related concussion, it is widely accepted that an individual will present with a prolonged reaction time due to an insult on the brain.\textsuperscript{3,5,7} With time, concussion-induced disruptions in neurocognitive and functional performance are often shown to gradually dampen, and an improvement in reaction time returns.\textsuperscript{1,8}

Furthermore, routine follow-up reaction time assessments are commonly performed and compared to an individual's pre-concussion (baseline) reaction time measures to determine post-concussion improvements in neurocognitive and functional health prior to an athlete being released for a return-to-play.\textsuperscript{5,7}

The assessment of reaction time has many benefits which include but are not limited to serving as a parallel indicator of one's central processing speed and cognitive function.\textsuperscript{5} Traditionally, qualitative evaluations of neurocognitive function and reaction time measures down to the millisecond have involved some form of computerized testing (e.g., software on a desktop computer with a keyboard and mouse).\textsuperscript{1,5,7,9} Computerized testing is known for its accuracy and reliability,\textsuperscript{5,10} however, are generally administered in a clinical setting and commonly criticized for their lack of portable practical application.\textsuperscript{5,9} Even laptops, which are viewed as a portable computerized device, require some set-up, along with an appropriate setting to successfully administer a cognitive and reaction time assessment. Such requirements complicate the feasibility of a portable on-field (i.e., athletic venues, athletic training room, military field hospital) assessment application. This is of concern because timely administration of cognitive and reaction time assessments are critical when assessing a potential on-field neuromotor injury.\textsuperscript{11} A delay in assessment may allow for misdiagnosis, which could result in harm or death of the patient or athlete. Therein, supports the need for a portable practical application to assess reaction time.

Mobile electronic devices such as smartphones and tablets are portable and user-friendly in most any setting (e.g., clinical, medical, and on-field). Most mobile electronic devices are also capable of operating mobile application software as well as administering various health and sport related assessment measures due to an inertial measurement unit (IMU) system built into the mobile device.\textsuperscript{12–14} IMUs measure specific force, angular velocity and sometimes the orientation of the body or movement of the device, using a combination of magnetometers, gyroscopes and triaxial accelerometers.\textsuperscript{12,15,16} In addition, mobile device applications can provide rapid biofeedback (e.g., neurocognitive measures, neuromotor measures, reaction time measures) based on the device IMU measures.\textsuperscript{12,16} Due to the portability and cognitive assessment application capabilities of a mobile device, use in assessing neurocognitive and neuromotor injuries has become of interest.\textsuperscript{5,9}

One such mobile device application is the Immediate Post-Concussion Assessment and Cognitive Test Quick Test (ImPACT QT). The ImPACT QT is an FDA cleared mobile device application developed to assess neurocognitive function following a suspected concussion.\textsuperscript{17} Due to its mobility and ease of use, the ImPACT QT is commonly used for sideline assessments in high school and collegiate athletics, as well as during routine clinical assessments.\textsuperscript{5,7,18} The five-minute ImPACT QT test includes a series of neurocognitive modules (symbol matching, three letter memory, reverse number counting, attention tracking) administered on a tablet screen. An individual’s rate of response (e.g., neurocognitive and reaction time measures) is recorded by touching the tablet screen following a visual prompt displayed on the display screen. During the assessment, the tablet may be held with both hands or placed on a flat surface while remaining in a standing posture. Following completion of the test, the ImPACT QT application provides three composite scores that may be compared against a subject’s previously established baseline measures.\textsuperscript{18,19} A decline in the composite scores is often used as an indication of a potential decline in neurocognitive function and consideration for removal of an individual from activity.\textsuperscript{6,19,20} Wallace and colleagues,\textsuperscript{19} however, caution of interpretation based on a single low score without cause of concern of a concussion because healthy non-concussive individuals have been shown to randomly present with an unexplained low score.

The ImPACT QT does present with a few limitations. First, the ImPACT QT is only compatible with an iOS (Apple, Cupertino, CA, USA) touch-screen iPad.\textsuperscript{6,19,20} An iPad, although well-accepted, is not the universal tablet among all end-users, nor clinical and athletic programs. This greatly marginalizes its accessibility and intended purpose of providing critical and often time sensitive sideline assessments. In addition, due to slower software and processor, the iPad is observed to have screen capacitance latency and test results are susceptible to a wider range of variability compared to a traditional desktop or laptop computer assessment. As screen latency can range from 50 to 200 milliseconds, latency induced variability may have an indirect effect on an individual’s true reaction time scores, potentially impacting clinical decisions.\textsuperscript{1,5,9,21–23} For example, if during an athlete’s baseline assessment screen was between 100 to 200 milliseconds, and was between 50 to 100 milliseconds during an on-field concussion assessment; the end result could be a missed or failed interpretation. The on-field assessment indicated a faster, although inaccurate reaction time measure in comparison to the athlete’s base-
line measure. Such inconsistencies due to latent variability of the iPad may place a patient-athlete at risk for another traumatic event that could potentially be more detrimental to neurocognitive function or even fatal. In addition, healthcare professionals may experience limitations in making an appropriate diagnosis when attempting to evaluate data comparisons between computer-aided testing and reaction time assessments administered on an iPad due to this wide range variability.

Recently, a new method for assessing cognitive function using a mobile device was introduced by SWAY Medical, Inc. The SWAY Cognitive Assessment (SWAY CA) mobile device application registers movement of the mobile device, instead of registering an applied touch screen response. The SWAY CA introduces a series of neurocognitive modules that evaluate an individual’s reaction time, inspection time, impulse control, and working memory-delayed recall. While an individual holds the device with both hands, a module prompts a visual cue on the display screen and evokes the individual to engage in or refrain from an active response (moving the device). An active response is recognized as a minimum motion-based threshold detected as the device is moved in any direction. The cognitive function and reaction time measures (time lapsed from the presence of a stimulus to the initiation of an action) for each of the three SWAY CA modules (simple reaction motion, impulse control, and inspection time) (see Methods section) are reported in milliseconds (ms) and a proprietary SWAY score calculated on a 100-point scale. The closer an individual’s score is to 100 the better one’s cognitive function and reaction time. The SWAY CA working memory-delayed recall module, however, is a single proprietary SWAY score based off lapsed time to recall, number of correct recall, and number of sequential squares tracked and recorded correctly.

To assess movement of the mobile device and interpret one’s rate of reaction time, SWAY CA’s proprietary algorithm uses a triaxial accelerometer motion-based system that is housed within the mobile device. Due to the orthogonal (right angles) placement of the three sensors in reference to each other, detection of device movement and vibration in any direction is registered with increased sensitivity compared to a system with less than three sensors. This increased sensitivity to motion has been shown to minimize mobile device latency down to one to two milliseconds. This is a pronounced improvement compared to touch-based reaction time mobile device detection with an average latency of 50 to 200 milliseconds. An additional advantage to SWAY CA is that it can be used on multiple platforms (smartphones and tablet) and is compatible with iOS (Apple, Cupertino, CA, USA) and Android (Samsung Group, Seoul, South Korea; Google, Mountain View, CA, USA) operating systems.

While the prospect of using mobile electronic devices as a clinical evaluation tool has many advantages, developers must ensure that their applications provide consistent results across all devices on which they are intended to operate. This is because, among the most popular smartphone and tablet devices, the number of different hardware and software combinations being used is numerous. Such differences may result in minor compatibility issues that impact processing speed, display screen refresh rate, and input latency. Additionally, different manufacturers may use different solutions for analyzing raw data from integrated sensors. Ultimate, for a mobile application to be versatile and provide clinically relevant and reliable assessments, it is essential to account for these differences across a spectrum of mobile devices and operating systems.

The purpose of this study was to assess whether the SWAY CA application (reaction time, impulse control and inspection time) was able to reliably operate on different mobile devices and operating systems (iOS, Android). The study further sought to assess the validity of the SWAY CA application against the FDA approved ImPACT QT mobile device application.

METHODS

SITE SELECTION

This study was completed in the Human Performance Laboratory (HPLab) at Wichita State University, Wichita, Kansas. This site was selected as the HPLab is experienced in the development and evaluation of mobile device applications.

PARTICIPANTS

A total of 90, college-aged individuals with a mean age of 22.09 ± sd = 4.42 years volunteered to participate in the study. An a priori power analysis was conducted using G*Power 3.1 software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) to identify appropriate sample size. To achieve a power of 0.80 with an α error of probability ≤ 0.05 and a medium effect size, a sample size of 84 participants was required. Volunteers were recruited through direct contact, and technology-based communication, as well as through print materials posted in public areas on the university campus. The Wichita State University Institutional Review Board approved the study, and an informed consent form was obtained from all volunteers prior to completing any questionnaire(s) or participating in data collection.

Inclusion and exclusion criteria. Any pre-existing condition that could interfere with successfully completing the assessment was identified based on the 2020 Physical Activity Questionnaire Plus (PAR-Q®). A participant was excluded from the study if they were under the age of 18 years, and were excluded if they reported any of the pre-existing conditions presented as follows; any current medical condition or medical history of a 1) musculoskeletal injury affecting functional movement and balance, 2) neurological dysfunction, 3) uncorrected vision, 4) vestibular disorder or condition, and/or 5) current, un-prescribed or prescribed pharmacological intervention affecting functional movement and balance.

Of the initial 90 volunteers, one participant was excluded for meeting one or more of the exclusion criteria. The remaining 89 participants met the intake questionnaire and were included in the study. One additional participant was removed from the study due to a technology error and inability to download the data output from the mobile device.
Overall, SWAY CA is completed in three to five minutes by
sure reaction time in reference to a known stimulus.

most mobile devices to detect motion
memory and reaction time.

cognitive processing speed, neuromotor response, working
neuromotor based modules to assess stimulus recognition,
SWAY System, SWAY CA, administers three sensor

tems, as well as deliver measures consistent in comparison
to the standardized ImPACT QT mobile application remain
validated. The cognitive performance segment of the
study. Mobile devices included:

For the remaining 88 participants, Table 1 provides the
demographic information (age, sex), as well as anthropometric
measures (height, weight) collected.

**SWAY MOBILE APPLICATION**

The SWAY System (SWAY Medical Inc., Tulsa, OK, USA) is a
mobile device application designed to assess balance (SWAY
Balance) and cognitive performance (SWAY CA) through the
use of different assessment modules. Both segments of the
SWAY System rely primarily on the analysis of movement, as
measured through the mobile device's integrated triaxial
accelerometer, to determine performance scores. Evaluation of the balance assessment
segment of the SWAY System has previously been reported
and received FDA Class II approval. The cognitive (re-
action time) testing segment has also been evaluated and
established clinically reliable and valid measures in com-
parison to the standard Computerized Test of Information
Processing (CTIP) assessment. However, SWAY CAs capac-
ity to execute on various mobile devices and operating sys-

tems, as well as deliver measures consistent in comparison
to the standardized ImPACT QT mobile application remain
to be validated. The cognitive performance segment of the
SWAY System, SWAY CA, administers three sensory and

dromotor based modules to assess stimulus recognition,
cognitive processing speed, neuromotor response, working

- Module 1 – Simple Reaction Time
  - Move the device as fast as one can in any direc-
tion when the screen of the device turns orange.
- Module 2 – Impulse Control
  - Move the device as quickly as possible when you
see a green check mark.
  - When you see a red X, keep the device still.
- Module 3 – Inspection Time
  - Two T-shaped lines will be shown on the device.
  - Once the two lines are masked (covered), you
will be instructed to move the device to the side
with the longer line.
  - Do not move the device if you are unsure which
line was longer. An incorrect response will re-
duce one's score.

SWAY CA utilizes tri-axial accelerometers built-in to
most mobile devices to detect motion and measure reaction
time in reference to a known stimulus. Overall, SWAY CA is completed in three to five minutes by

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**Table 1. Subject Demographic Information**

<table>
<thead>
<tr>
<th></th>
<th>Male (n = 32)</th>
<th>Female (n = 56)</th>
<th>Total (N = 88)</th>
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<tr>
<td><strong>Age (years)</strong></td>
<td>22.38 ± 5.68</td>
<td>21.93 ± 3.63</td>
<td>22.09 ± 4.46</td>
</tr>
<tr>
<td><strong>Stature (cm)</strong></td>
<td>178.73 ± 8.27</td>
<td>167.25 ± 7.42</td>
<td>171.43 ± 9.49</td>
</tr>
<tr>
<td><strong>Weight (kg)</strong></td>
<td>83.25 ± 14.9</td>
<td>76.25 ± 20.26</td>
<td>78.79 ± 18.72</td>
</tr>
</tbody>
</table>

n = Sum of sample, N = Sum of total sample, cm = Centimeters, kg = Kilograms

---

IMPACT QUICK TEST MOBILE APPLICATION

The ImPACT QT (ImPACT Applications, Inc., San Diego, CA,
USA) is an FDA approved iPad-based neurocognitive test
designed for clinical use (e.g., concussion baseline mea-
sures, pre- and post-neurocognitive injuries (concussion as-
essment)). ImPACT QT administers three neurocognitive
modules to assess basic output related to
neurocognitive functioning, working memory, processing
speed, reaction time and symptom recording in a brief five-
seven minutes. The three neurocognitive modules are
as follows.

- Module 1 – Symbol Matching
  - Trial 1: Match shapes with numbers using the
touch screen as quickly as you can.
  - Trial 2: Remember which shape goes with what
number using the touch screen as quickly as you
can.
- Module 2 – Three Letter Memory and Reverse Num-
ber Counting
  - Trial 1: Count backwards from 25 to 1 using the

---

**International Journal of Sports Physical Therapy**
Table 2. Means and Standard Deviations of SWAY CA Simple Reaction, Impulse Control and Inspection Time by Mobile Device

<table>
<thead>
<tr>
<th>Mobile Device</th>
<th>Simple Reaction</th>
<th>Impulse Control</th>
<th>Inspection Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPad</td>
<td>75.38 ± 0.00</td>
<td>59.58 ± 0.00</td>
<td>92.50 ± 0.00</td>
</tr>
<tr>
<td>iPhone 6S</td>
<td>73.91 ± 7.56</td>
<td>61.85 ± 7.15</td>
<td>81.73 ± 18.27</td>
</tr>
<tr>
<td>Google Pixel 3</td>
<td>71.45 ± 8.15</td>
<td>54.34 ± 0.08</td>
<td>97.50 ± 3.54</td>
</tr>
<tr>
<td>Samsung Galaxy S9</td>
<td>74.73 ± 7.61</td>
<td>62.76 ± 6.72</td>
<td>86.09 ± 13.24</td>
</tr>
</tbody>
</table>

The ImPACT QT test was administered utilizing an Apple iPad Pro 5, [Software Version – 12.1.1 (16C50), Model: MR7F2LL/A, Serial: DMR Y26GRJF8J and Serial: DMRY236PJF8J (Apple Computer Inc., Cupertino, CA, USA)]. For each module, instructions were provided on the device screen as well as each participant was provided verbal instruction from an experienced research administrator. Participants were instructed to lay the device flat on the countertop surface and maintain a standing position while performing each module.

Procedure. Each participant completed a total of four cognitive assessments (two SWAY CA and two impact QT). Following a similar protocol described in detail in a previous study for balance by Amick and colleagues,²⁸ each participant completed one familiarization trial and one experimental (baseline) trial for each application (SWAY CA, ImPACT QT). To control for a learning effect and bias, participants were issued one of the four previously described preloaded SWAY CA application mobile devices, and a preloaded ImPACT QT iPad in a randomized order. In addition, the order of the two application cognitive assessments (SWAY CA, ImPACT QT) was counter-balanced (e.g., SWAY – ImPACT QT – SWAY – ImPACT QT, or ImPACT QT – SWAY – ImPACT QT – SWAY). Each participant was provided a two-three-minute seated rest period between test applications. The research administrator used a stopwatch to maintain consistent rest periods.

DATA ANALYSIS

Statistical analysis was conducted using the Statistical Packages for the Social Science (SPSS) version 23.0 with a level of significance set at α ≤ 0.05 and a confidence level of 95%. All test variables were evaluated for normality of distribution.

Three separate one-way analyses of variance (ANOVA) were conducted to determine group mean difference of Mobile Device (iPhone 6s Plus, Google Pixel 3, Samsung S9, iPad Pro 5) on each of the SWAY CA baseline measures (simple reaction, impulse control, inspection time). The critical alpha level for each ANOVA was set at p ≤ 0.05. A post-hoc test was completed at p ≤ 0.05 if a significant mean difference was reported.

A Pearson’s Product Moment Correlation Coefficient (r) was conducted to determine the degree of correlation in baseline SWAY CA measures (simple reaction motion, impulse control, inspection time) and the ImPACT Quick Test application battery of modules at a p ≤ 0.05. The Coefficient of Determination (r²) was further calculated to determine the amount of shared variance between the SWAY CA and ImPACT QT scores. A Pearson’s Product Moment Correlation Coefficient Interpretation as follows, weak r = 0.00 to 0.30, moderate r = 0.31 to 0.59, and strong r = 0.60 to 1.00.⁷,¹⁷

RESULTS

All SWAY CA and ImPACT QT measures were inspected and found to fall within an acceptable range and demonstrated a normal distribution. Table 2 provides the means and standard deviations of each SWAY CA measure (simple reaction, impulse control, inspection time) by mobile device (iPad, iPhone 6S, Google Pixel 3 and Samsung Galaxy 9S).

A one-way analysis of variance (ANOVA), as shown in Figure 1, determined SWAY CA Simple Reaction mean difference did not significantly differ between Mobile Devices.

Figure 1. Mean difference in SWAY CA Simple Reaction Motion, Impulse Control, and Inspection Time Measures between Mobile Devices

* No significant difference reported, p > 0.05
Table 3. Total Number of SWAY CA and ImPACT QT Assessments by Mobile Device

<table>
<thead>
<tr>
<th>Device</th>
<th>SWAY CA</th>
<th>ImPACT QT</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPhone</td>
<td>46</td>
<td>88</td>
</tr>
<tr>
<td>Google Pixel</td>
<td>2</td>
<td>88</td>
</tr>
<tr>
<td>Samsung</td>
<td>39</td>
<td>88</td>
</tr>
<tr>
<td>iPad</td>
<td>1</td>
<td>88</td>
</tr>
<tr>
<td>Total</td>
<td>88</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 4. Summary of Bivariate Correlations Between SWAY CA and ImPACT QT Measures

<table>
<thead>
<tr>
<th>SWAY CA</th>
<th>ImPACT QT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simple Reaction Motion</td>
</tr>
<tr>
<td>Visual Motor Speed</td>
<td></td>
</tr>
<tr>
<td>Three Letter Count Correct</td>
<td>0.22</td>
</tr>
<tr>
<td>Reaction Time</td>
<td></td>
</tr>
<tr>
<td>Three Letter Time First Click</td>
<td>-0.08</td>
</tr>
<tr>
<td>Rectangular Average Time</td>
<td>-0.44</td>
</tr>
<tr>
<td>Figure Eight Average Time</td>
<td>-0.46</td>
</tr>
<tr>
<td>Complex Average Time</td>
<td>-0.32</td>
</tr>
<tr>
<td>Symbol Match Correct Visible</td>
<td>-0.27</td>
</tr>
<tr>
<td>Symbol Match Correct Hidden</td>
<td>-0.35</td>
</tr>
<tr>
<td>Symbol Match Incorrect Hidden</td>
<td>-0.32</td>
</tr>
</tbody>
</table>

Bolded values represent $p < 0.05$

$F (3, 84) = 0.182, p = 0.91, \eta^2_p = 0.01$. One-way ANOVA, as shown in Figure 1, determined SWAY CA Impulse Control mean difference did not significantly differ between mobile devices, $F (3, 84) = 1.02, p = 0.39, \eta^2_p = 0.04$. In addition, the one-way ANOVA, as shown in Figure 1, determined SWAY CA Inspection Time mean difference did not significantly differ between mobile devices, $F (3, 84) = 1.08, p = 0.36, \eta^2_p = 0.04$. Post-hoc tests were not administered based on the lack of significant differences found between mobile devices for each of the SWAY CA measures. As shown in Table 3, it is important to address that Google Pixel 3 ($n = 2$) and the iPad Pro 5 ($n = 1$) each reported a very small group sample and will be further addressed in the discussion.

As shown in Table 4, a Pearson Product Moment Bivariate Correlation Coefficient ($r$) determined that SWAY CA simple reaction motion was negatively correlated, weak to moderate, across all seven ImPACT QT reaction time measures ($r = -0.08$ to $-0.46$), however three letter time first click was the only measure not found to be significant at $p \leq 0.05$. In addition, the three letters counting correct mean score of the ImPACT QT visual motor speed module was found to have a weak positive correlate with the SWAY simple reaction motion ($r = 0.22, p < 0.05$). SWAY CA impulse control was found to have a significant negative correlation ($p \leq 0.05$) of moderate strength with ImPACT QT attention tracker rectangular average time correct ($r = -0.46$), attention tracker figure eight average time correct ($r = -0.36$), and attention tracker complex average time correct ($r = -0.31$), respectively. The remaining ImPACT QT measures, however, were not found to correlate with SWAY CA Impulse Control ($p > 0.05$), as indicated in Table 4. SWAY CA inspection time was found to have a significant negative correlation of weak strength with ImPACT QT attention tracker figure eight average time correct ($r = -0.29$), and symbol match incorrect hidden average answer time ($r = -0.25$). However, SWAY CA inspection time was not found to correlate with the remaining ImPACT QT measures ($p > 0.05$) (Table 4).

DISCUSSION

This study sought to determine the validity of the SWAY CA application, as well as its reliability across various hardware platforms and operating systems. The results indicated that SWAY CA application appears to be reliable in operating cognitive assessment measures (simple reaction motion, impulse control, inspection time) on various mobile devices (i.e., iPhone 6s Plus, Google Pixel 3, Samsung S9, and iPad Pro 5) and operating systems (e.g., iOS, Android). Such findings are important because this introduces the feasibility of assessing neurocognitive function and reaction time measures regardless of the mobile device avail-
able. Although the SWAY CA measures across all mobile devices were found to be in agreement; the iPad Pro 5 and Google Pixel 3 each offered a rather small contribution to the overall analysis. The iPad has been shown to be a valid and compatible mobile device for the SWAY application’s balance segment and did not present with any compatibility concerns when in use with the SWAY reaction time segment. The small sample size of the iPad Pro 5 (n = 1) was due to its lack of availability, as it was also being used to administer the ImPACT QT during experimental testing sessions. The Google Pixel 3, however, presented with a login issue that resulted in limited SWAY CA assessments (n = 2) and generally inconclusive findings of its compatibility. Overall, the SWAY CA application introduces the convenience of mobility and mobile device versatility, unlike the ImPACT QT application that requires the adoption of a universal mobile device. Furthermore, the lack of significant difference in SWAY CA measures between mobile devices minimizes concern of a difference in an individual’s SWAY CA measures (e.g., comparison of baseline data to data recorded immediately following an insult, and each follow-up assessment) being due to the use of different mobile devices.

The findings of this study further indicated that the SWAY CA segment of the SWAY System is a valid tool for assessing reaction time. Based on correlation values established between the measures using the SWAY system and the ImPACT QT, (0.32 to 0.65, p = 0.05) the Simple Reaction Motion of the SWAY CA application introduced reaction time measures (-0.27 to -0.46, p < 0.05) comparable with reaction time measures of the ImPACT QT reaction time measures, except three letter time click first. The lack of agreement of the SWAY CA simple reaction motion measure with the ImPACT QT three letter time click first measure, as shown in Table 4, may be due to the difference in task(s) administered by each application to assess and calculate the measure as previously described in the methods section. Overall, these findings suggest that the SWAY CA is a comparable mobile neurocognitive and reaction time assessment tool to the FDA approved ImPACT QT.

In addition, several SWAY CA simple reaction motion, impulse control, and inspection time measures reported a negative correlation (-0.25 to -0.46; p < 0.05) in relation to the ImPACT QT reaction time measures. Both SWAY CA and ImPACT QT measure rate of response based on lapse in time (milliseconds) from the moment a stimulus is introduced to the moment a response is recorded. The negative correlational values introduced in this study indicate that, on average, an individual’s rate of response milliseconds following a stimulus was significantly faster (smaller value) with the motion-based system used for SWAY CA in comparison to the slower (greater value) recorded when using the touch-based system for the ImPACT QT. Relatedly, these findings align with previous studies that reported motion-based systems (i.e., SWAY) to be extremely sensitive in recognizing movement as well as minimize mobile device latency down to one to two milliseconds, compared to a 50 to 200 millisecond delay when using a touch-based system (i.e., ImPACT QT). Of additional importance, hardware specifications between the devices used to administer the two applications differ (SWAY, ImPACT QT). The processors for each of the devices ran the respective operating systems at between 1.8 and 2.5 gigahertz. The screen on the iPhone 6S, Samsung 9s, and the Google Pixel 3, however, which were used to administer all but one of the SWAY application assessments, have a refresh rate of 60hz, compared to double the refresh rate of the iPad Pro 5 screen at 120hz used to administer the ImPACT QT application. Interestingly, although all SWAY assessments, except the one iPad Pro 5 measure, operated off a device with a slower refresh rate, the SWAY application was shown to recognize and capture a reaction time movement or cognitive response at a faster rate compared to the ImPACT QT based on the negative correlational findings. These findings further support the superior sensitivity of the motion-based SWAY application when seeking to record an individual’s reaction time measures and further assess one’s neurocognitive function and health. This is of particular importance for an individual in sport or other clinical setting where cognitive and reaction time measures may have critical and potentially life-threatening implications.

While measures of agreement between the SWAY CA and ImPACT QT applications were established across several measures; further investigation is needed to determine the fair to low correlation amongst many of the SWAY impulse control and inspection time measures with the ImPACT reaction time and visual motor speed measures, as indicated in Table 4. One consideration for this absence of agreement may be due to distinct differences in measurement design for a particular assessment. Although both applications include assessment of reaction time measures; the SWAY application is a cognitive assessment tool that evaluates an individual’s cognitive and neuromotor measures, while the ImPACT QT application is known as a post-concussion cognitive test recognized as a neurocognitive and reaction time assessment tool. Therein, the impulse control and inspection time measures of the SWAY may differ beyond comparison with the ImPACT QT more so due to the measurement approach each uses. An additional consideration may be the notable difference in latency and electrical pulse cycle between the application operating systems. As shown in Table 4, the faster response rate of the motion-based system of SWAY compared to the slower touch-based system of the ImPACT QT may help explain the lack of associated strength amongst some of the measures and absence of agreement for others. Future test-retest reliability is warranted to further validate; however, the current findings support the use of a motion-based approach and the SWAY application to assess cognitive function and reaction time measures on a mobile device.

LIMITATIONS AND FUTURE DIRECTIONS

This study is the first effort to establish concurrent validity of the cognitive assessment modules of the SWAY application as well as its capacity to operate across multiple mobile devices. Overall, the SWAY application was found to deliver reliable and valid cognitive and reaction time measures across all mobile devices; however, the iPad was only used to administer one SWAY assessment and the Google Pixel 3 did present with some concerns. The lack of data...
recorded from the iPad was due to lack of availability of the device because it was also being used to administer the ImPACT QT. The inclusion of the iPad in future studies is necessary to determine its compatibility with SWAY CA, as well as the potential impact of iPad latency of scores as previously discussed. It is unknown, however, whether the sporadic error message displayed during login and download when using the Google Pixel 3 was a compatibility issue or related to some other unknown. This unknown will require future exploration to determine.

Furthermore, the current findings should be generalized across all mobile device systems (hardware, software) with caution due to known capacity differences across systems as potentially indicated with the Google Pixel 3. In addition, as mobile device systems, including the devices in this study, frequently introduce updates to the hardware and software, further verification of SWAY compatibility is necessary. In addition, while the findings of this study supported the concurrent validity of the SWAY’s ability to yield consistent cognitive and reaction time measures comparable to those of the FDA approved ImPACT QT; further test-retest reliability to determine within intrasession reliability and between intersession reliability is necessary.

CONCLUSION

In conclusion, the results of the current study indicate that the SWAY application is a reliable and valid method for measuring cognitive and reaction time measures across a variety of mobile devices. Furthermore, the faster capture rate technology used by the motion-based SWAY application appears to offer a potentially more reliable assessment of cognitive function and reaction time in comparison to the FDA approved touch-based ImPACT QT measures. Additionally, the SWAY application’s versatility in operating across various mobile device systems may further support its favorability of use in both health and sport.

CONFLICT OF INTEREST

Authors have no reported conflicts of interest.

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REFERENCES


Original Research

Safety and Effectiveness of a Perturbation-based Neuromuscular Training Program on Dynamic Balance in Adolescent Females: A Randomized Controlled Trial

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Keywords: anterior cruciate ligament, functional testing, movement system

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Background
Adolescent females are at much greater risk for ACL injury than their male counterparts when participating in the same sports. Preventative and pre-operative rehabilitation neuromuscular (NM) exercise programs are often recommended to improve knee function and reduce injury rates. The effectiveness of perturbation-based NM training program has been established in an adult population but has yet to be investigated in the at-risk adolescent female population.

Purpose
To determine the effectiveness of a perturbation-based NM exercise program in a group of physically active adolescent females.

Study Design
Prospective randomized trial.

Methods
Twenty-four healthy and an exploratory group of 10 ACL-injured females (ages 12-18) were equally randomized into a perturbation-based NM training or control group and evaluated before and after a five-week intervention period. The primary outcome of dynamic balance was measured using the Y-Balance test (YBT); secondary outcome measures included lower limb strength, proprioception, and flexibility.

Results
The perturbation-based NM training intervention was safely completed by all participants but had no significant effect on YBT scoring, lower limb strength, proprioception or flexibility in either the healthy or ACL-injured groups.

Conclusions
Perturbation-based NM training is safe, but may offer little preventative benefit for healthy or pre-operative rehabilitation benefit for ACL-injured adolescent females. Future research should examine whether the effectiveness of perturbation-based NM training is influenced by the length of the training intervention, training intensity, or when it is combined with other forms of prophylactic or pre-surgical rehabilitation frequently used with at-risk adolescent females who regularly participate in sport.

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Level of Evidence
Level 3.

INTRODUCTION

Rupture of the anterior cruciate ligament (ACL) is one of the most common knee injuries, with an estimated 250,000 ACL ruptures documented per year in North America.¹ It is also the most commonly injured knee ligament in a pediatric population,²,³ with its incidence growing fastest in physically active adolescents (14 – 18 years old) participating in high school sports.⁴ While an ACL injury is a significant risk for both sexes, adolescent females have a 1.6-fold greater rate of ACL injury per athletic exposure than adolescent males participating in the same sports.⁴,⁵

In North America, the standard of care for young patients following ACL rupture is surgical reconstruction.⁶,⁷ Early surgical repair is especially favored for adolescent patients because it helps to restore joint stability, reduces the incidence of secondary joint injury, and promotes return to pre-injury levels of physical activity.⁸ However, skeletal immaturity⁹ and long surgical wait times¹⁰ can result in significant delays in the injury-to-surgery time line. The average injury-to-surgery wait time following ACL injury within a local Canadian regional health authority has been documented to be as high as 458 days.¹⁰ As a result, pre-operative exercise programs are frequently prescribed for patients awaiting ACL reconstructive surgery,¹¹,¹² as they are thought to help re-establish the normal kinetic and kinematic function of the affected joint. Superior functional outcomes and higher return-to-sport rates have been reported for adult patients who participated in rehabilitation programs that included perturbation-based neuromuscular training as part of a pre-operative treatment regimen.¹³

Neuromuscular (NM) training is designed to improve dynamic joint stability, generate fast and optimal muscle activation, and decrease joint forces. It forms a critical aspect of injury prevention exercise programs that are designed to reduce the costs and morbidity associated with ACL injury in young athletes.¹⁴ In addition to reducing the rate of ACL ruptures in female adolescents by approximately 50%,¹⁵–¹⁸ research suggests that NM training during early adolescence can improve lower extremity performance¹⁹,²⁰ and dynamic balance.²¹–²⁴ While the specific exercises included in an NM training regime can vary greatly, NM programs typically include some form of plyometric single-leg hopping, jumping, pivoting, or cutting maneuvers that are considered unsafe or impractical for use with an ACL-injured individual.¹⁵–²⁰,²⁵–²⁹

Perturbation-based NM training regimens are designed to be safe and effective for ACL-injured patients as part of a pre-operative exercise program.³⁰ They typically include exercises that require the patient to maintain their balance on a support surface while a clinician deliberately perturb (i.e., manipulates) the support system.³¹ Research targeting an ACL-injured adult population indicates that perturbation-based NM training is effective for improving knee joint kinematics, gait patterns, subjective functional outcomes and return-to-sport rates.¹³,³¹–³⁸ Unfortunately, the safety and effectiveness of a perturbation-based NM training regime in an at-risk adolescent female population is unreported in the literature.

The purpose of this investigation was to determine the effectiveness of a perturbation-based NM exercise program in a group of physically active adolescent females. The primary outcome measure was dynamic balance, while lower limb strength, proprioception, and flexibility were outcome measures of secondary interest. Program safety was assessed by evaluating the number and severity of injuries sustained by subjects. The authors hypothesized that completion of a perturbation-based NM exercise program would improve 1) dynamic balance and 2) lower extremity strength, proprioception and flexibility in physically active adolescent females.

METHODS

PARTICIPANTS

Following institutional ethics approval (H2014:302), healthy and ACL-injured physically active adolescent females were recruited from the community. Inclusion criteria stated that healthy volunteers were required to be female, 12-18 years of age, with no history of any lower limb injury or concussions in the past 6 months. A group of subjects awaiting ACL surgical repair were recruited from a community-based orthopaedic clinic to participate in this clinical study following the same inclusion criteria (Figure 1). Subjects were evaluated clinically by an orthopaedic surgeon and the diagnosis of an isolated ACL rupture (without secondary injury to meniscal or chondral surfaces) was confirmed via magnetic resonance imaging. Participants were excluded if they were unable to attend either the testing or training sessions or if they failed an established standardized screening protocol at the beginning of the study. A participant was scored as a “failure” and excluded from study participation if they presented with knee joint effusion, were unable to fully flex and extend the knee joint though a full range of motion, had quadriceps lag with an active straight-leg raise, had isometric quadriceps strength less than 75% of the unaffected leg measured via manual muscle testing or were unable to perform 10 consecutive single-legged hops pain free.³⁰

TESTING PROTOCOL

Prior to participation, informed consent was obtained from all girls and their parents. Anthropometric data including height, weight, and body mass index (BMI) were recorded. Bilateral knee joint laxity was evaluated using the KT-1000 (MEDmetric Corp.; San Diego, CA).³⁹ Demographic information, including age, maturation status determined by using the self-reported pubertal maturation observational scale (PMOS),⁴⁰ leg dominance (determined by leg preference for kicking a ball), and type of sport participation were collected. Participants were then equally randomized into 2 groups (perturbation-based NM training or control) using pre-coded envelopes that were assigned to each partic-
icipant. Baseline measurements for dynamic balance, lower limb strength, proprioeception, and flexibility were completed on all participants. Participants randomized to the intervention group completed a 5-week perturbation-based NM training regime while the participants randomized into the control group were instructed to continue with their normal activities. All participants returned for follow-up evaluation.

**DYNAMIC BALANCE MEASUREMENT**

To measure dynamic balance, the Y-Balance Test (YBT) (Move2Perform; Evansville, IL) was completed according to previously described protocols. The distance from the YBT apex of the most proximal edge of the reach indicator was recorded while participants performed movement in three directions: anterior (ANT), posteromedial (PM) and posterolateral (PL). The average of 3 successful trials for each reach direction was used for analysis. All reach distances were normalized as a percentage of each participant’s stance-limb length (%LL), measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine, lying position.

**LOWER LIMB STRENGTH EVALUATION**

Hand-held dynamometry (HHD) is a valid, reliable measure of isometric muscle strength in adolescents and an ideal test method for use when evaluating lower extremity strength in a clinical setting. The ”make-test” method was used because it is preferred for use with adolescents: the examiner held the dynamometric instrument (Chatillon DFX II Series; Largo, FL) in a stationary position while the subject gradually built resistance for a 5-second push against the dynamometer. Standardized positions were used to assess strength during knee flexion, knee extension, hip external rotation, hip abduction, and ankle plantar flexion movements. Strength scores for each movement were determined by calculating the average of three HHD measurements for each movement. Strength scores for each subject were then expressed as HHD force (N) relative to body weight (kg).

**KNEE PROPRIOCEPTION EVALUATION**

Joint-position sense (JPS) - the awareness of limb position in three dimensions - is a common proprioceptive test routinely used during weight bearing (WB) activity to provide a functional evaluation with greater clinical relevance for conditions such as ACL instability. Using previously described methodologies, the WB-JPS for each participant was assessed. Briefly, with eyes closed and while maintaining a unilateral stance, each subject was instructed to slowly flex the knee of the WB limb and to stop at approximately 30 degrees of flexion - the test angle (TA). An electro-goniometer (Acumar Dual Inclinometer ACU0002, Lafayette Instrument Company; Lafayette, IN) was then used to confirm the exact knee-joint angle. The TA was held for approximately 5 seconds, after which the subject was directed to return to a position of full knee extension and bilateral stance. The subject was then asked to reproduce the same amount of unilateral knee flexion - response angle (RA). Absolute angular error (AAE) is the absolute arithmetic difference between the TA and RA scores. All subjects repeated the WB-JPS test three times, with the average AAE for each limb being used for analysis.

**LOWE R EXTREMIT Y FLEXIBILITY EVALUATION**

Hamstring and calf muscle flexibility were evaluated using joint-specific tests executed according to previously established protocols. A standing toe-touch test was used to access hamstring flexibility. Briefly, subjects stood on a step-stool with their feet hip-width apart and were instructed to keep their knees, arms and fingers straight while they bent forward as far as possible. The maximum reach position (held for a minimum of 6 seconds) was measured to the nearest 0.5 cm. The average of three trials was used for analysis. Calf muscle flexibility was determined using the weight-bearing lunge test (WBLT). Briefly, while in a standing position facing a wall, subjects were instructed to keep their test heel on the floor while flexing their knee to touch the wall in front of them. The maximum reach position was determined by measuring the distance from the great toe to the wall (measured to the nearest 0.5 cm) while maintaining heel and knee contact. After three practice trials, subjects completed three test trials, the average of which was used for analysis.

**PERTURBATION-BASED NM EXERCISE REGIME**

Participants randomized to the perturbation-based NM training group completed two supervised training sessions per week for five consecutive weeks (for a total of 10 sessions). This validated training program was administered according to a previously established procedure (Appendix). In brief, a series of destabilizing perturbations were applied during either unilateral or bilateral stance on each of three unstable surfaces (rollerboard, rollerboard and rollerboard/platform). Over the five-week training regime, application of the destabilizing force pro-
gressed in a standardized manner from an informed unilateral direction (slow and low in magnitude), to an unexpected, rapid application of destabilizing forces in random directions with sport-related distractions (catching and throwing a ball at the same time performing balance activity).

STATISTICAL ANALYSIS

A power analysis based on scoring from previous investigations that examined dynamic balance in a healthy group of recreationally active adults indicated that a total of 11 subjects per group would be required for the current investigation.68,59 Following the recommendation of a previous report,60 the dominant limb of all healthy participants and the affected limb of the ACL-injured participants was used for analysis. SPSS for Windows 24.0 (SPSS Inc.; Chicago, IL) was used for analysis. One-way analysis of variance (ANOVA) was used to test the differences in baseline demographic and anthropometric data between perturbation and control groups for each of healthy and ACL-injured groups. Two-way ANOVAs were used to compare baseline and follow-up scoring on dynamic balance, proprioception, flexibility, and strength. A post hoc Bonferroni correction of \( p \leq 0.008 \) was set to determine statistical significance. A Fisher’s exact test was used to examine the relationship between the group (control or perturbation training) and clinically significant improvements in each YBT reach direction. The level of statistical significance was set at \( p \leq 0.05 \) while a clinically significant improvement was classified as greater than 8.54%, 13.50% and 13.70% for the ANT, PM and PL reach directions, respectively.61

RESULTS

Table 1 provides descriptive data for participant demographics and anthropometry. Baseline data indicated that there were no significant differences between control and perturbation groups on the demographic and anthropometric data between groups. However, the ACL-injured control group was significantly older than both healthy-perturbation and healthy-control groups. Knee joint laxity for both the ACL-injured control and perturbation groups was also significantly greater than both of the healthy groups – as would be expected. For ACL-injured participants, the mean time from injury to the baseline examination was 143 days (range: 24-365). Over the duration of the study, there were no significant changes in weight, or BMI for any of the groups. Results suggested that participants in each group were predominantly post-pubertal adolescents who were right leg dominant and participated in a variety of sporting activities.

All participants completed both testing sessions and the mean time from the initial assessment to follow-up assessment was 41 days (range: 30-47). All subjects (healthy and ACL-injured) randomized to the perturbation group safely completed the training program without any incidence of pain, swelling or knee instability. The training program included 10 sessions; the mean number of completed sessions was nine (range: 7-10). On average, each training session was completed in approximately 30 minutes and the 10 training sessions took place over an average of 31 days (range: 21-35). No subjects randomized to the training group reported any incidence of knee joint pain, swelling or instability while participating in the training program exercises or at the follow-up assessment.

Comparisons of baseline and follow-up test scores for the YBT are presented in Figures 2 through 4 for healthy and ACL-injured subjects.
Table 1. Demographic and anthropometric information for all subjects, reported as mean ± SD, (95% confidence interval).

<table>
<thead>
<tr>
<th></th>
<th>Healthy (n=24)</th>
<th>ACL-injured (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control (n=12)</td>
<td>Perturbation (n=12)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>13.9 ± 1.1 (13.2, 14.6)</td>
<td>14.3 ± 1.5 (13.3, 15.2)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>161.8 ± 6.2 (157.9, 165.7)</td>
<td>164.5 ± 5.5 (161.0, 168.0)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>54.3 ± 10.8 (47.4, 61.2)</td>
<td>63.3 ± 17.7 (52.0, 74.5)</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>20.6 ± 3.2 (18.6, 22.6)</td>
<td>23.3 ± 5.4 (19.9, 26.7)</td>
</tr>
<tr>
<td>Knee Laxity Difference (mm)</td>
<td>1.5 ± 1.1 (0.8, 2.2)</td>
<td>1.5 ± 1.0 (0.8, 2.1)</td>
</tr>
<tr>
<td>Time since injury (months)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Leg Dominance – Right, n</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Developmental status, n</td>
<td>Pre-pubertal</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mid-pubertal</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Post-pubertal</td>
<td>7</td>
</tr>
<tr>
<td>Sport (n)</td>
<td>Basketball</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Badminton</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Baton</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Dance</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Cross country running</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Gymnastics</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Hockey/Ringette</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Rugby</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Soccer</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Softball</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tennis</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Volleyball</td>
<td>1</td>
</tr>
</tbody>
</table>

*Significantly different than the healthy control (p<0.001) and healthy perturbation (p=0.002)
†Significantly different than the healthy control (p=0.006) and healthy perturbation (p=0.005)
‡Significantly different than the healthy control (p=0.001) and healthy perturbation (p=0.001)

reach direction, follow-up test scores of the healthy participants were significantly larger for both the control and perturbation training groups (time effect: p≤0.008), while there were no significant differences between baseline and follow-up scores for either of the ACL-injured groups (Figure 2). The YBT data for PL & PM reach directions indicated that regardless of group allocation (control or perturbation), follow-up test scores of both the healthy and ACL-injured groups were significantly larger than scoring from baseline testing (time effect: p≤0.008) (Figures 3 and 4).

The results of the Fisher’s exact test for the YBT are presented in Table 2. For both the healthy and ACL-injured subjects, no clinically significant differences (p>0.05) were found between the control and perturbation training groups for any of the reach directions.

Strength measurements for the healthy participants indicated a statistically significant improvement in hip abduction strength following completion of the perturbation-based NM training regime; however, the improvement was not clinically significant. All other changes for both groups were not statistically significant, and data suggested that participation in the perturbation-based NM exercise program had no significant effect on strength scores for both the healthy and ACL-injured participants (Tables 3 and 4).

Finally, proprioception and flexibility measurements indicated that there were no significant differences in scoring when comparing both the control or perturbation groups at baseline or follow-up, or when examining the effect of the perturbation-based NM exercise regime on either the healthy or ACL-injured participants (Tables 5 and 6).
Table 2. Numbers of healthy participants having reached clinically significant* improvements in each Y-balance test (YBT) reach direction.

<table>
<thead>
<tr>
<th></th>
<th>Healthy (n = 24)</th>
<th></th>
<th>ACL-injured (n=10)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Perturbation</td>
<td>p value</td>
<td>Control</td>
</tr>
<tr>
<td>Control (yes/no)</td>
<td>1/11</td>
<td>1/11</td>
<td>1.0</td>
<td>0/5</td>
</tr>
<tr>
<td>Perturbation (yes/no)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Clinically significant improvement was classified as ANT >8.54%, PM >13.50% and PL >13.70%; * p≤0.05

Table 3. Strength measurements for the healthy subjects, reported as mean ± SD, (95% confidence interval).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=12)</th>
<th></th>
<th>Perturbation (n=12)</th>
<th></th>
<th>p-value^a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Follow-up</td>
<td>Initial</td>
<td>Follow-up</td>
<td>Time</td>
</tr>
<tr>
<td>Knee Flexion (N/kg)</td>
<td>3.7 ± 0.6</td>
<td>(3.3, 4.1)</td>
<td>3.8 ± 0.6</td>
<td>(3.4, 4.2)</td>
<td>2.9 ± 0.6</td>
</tr>
<tr>
<td>Knee Extension (N/kg)</td>
<td>5.4 ± 1.3</td>
<td>(5.6, 6.2)</td>
<td>5.8 ± 1.2</td>
<td>(5.0, 6.6)</td>
<td>4.8 ± 1.1</td>
</tr>
<tr>
<td>Hip External Rotation (N/kg)</td>
<td>2.1 ± 0.5</td>
<td>(1.8, 2.4)</td>
<td>2.3 ± 0.4</td>
<td>(2.0, 2.5)</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>Hip Abduction (N/kg)</td>
<td>2.0 ± 0.4</td>
<td>(1.7, 2.2)</td>
<td>1.8 ± 0.3</td>
<td>(1.6, 2.0)</td>
<td>1.7 ± 0.3</td>
</tr>
<tr>
<td>Ankle Plantarflexion (N/kg)</td>
<td>5.9 ± 1.3</td>
<td>(5.1, 6.7)</td>
<td>5.7 ± 1.2</td>
<td>(4.9, 6.5)</td>
<td>5.7 ± 1.3</td>
</tr>
</tbody>
</table>

^a Findings from multivariate analysis of variance
* Lower than the Control initial (p=0.003) and follow-up (p=0.002) groups.
† Increased from initial to follow-up for all groups
‡ Control group decreased and perturbation group increased

Table 4. Strength measurements for the ACL-injured subjects, reported as mean ± SD, (95% confidence interval).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=5)</th>
<th></th>
<th>Perturbation (n=5)</th>
<th></th>
<th>p-value^a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Follow-up</td>
<td>Initial</td>
<td>Follow-up</td>
<td>Time</td>
</tr>
<tr>
<td>Knee Flexion (N/kg)</td>
<td>3.1 ± 1.1</td>
<td>(1.7, 4.5)</td>
<td>3.6 ± 1.1</td>
<td>(2.2, 5.0)</td>
<td>2.7 ± 0.3</td>
</tr>
<tr>
<td>Knee Extension (N/kg)</td>
<td>5.0 ± 1.8</td>
<td>(2.8, 7.2)</td>
<td>5.6 ± 1.4</td>
<td>(3.9, 7.3)</td>
<td>4.5 ± 0.5</td>
</tr>
<tr>
<td>Hip External Rotation (N/kg)</td>
<td>1.9 ± 0.7</td>
<td>(1.0, 2.8)</td>
<td>2.1 ± 0.7</td>
<td>(1.2, 3.0)</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>Hip Abduction (N/kg)</td>
<td>1.5 ± 0.3</td>
<td>(1.1, 1.9)</td>
<td>1.5 ± 0.3</td>
<td>(1.1, 1.9)</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>Ankle Plantarflexion (N/kg)</td>
<td>5.4 ± 1.4</td>
<td>(3.7, 7.1)</td>
<td>5.6 ± 1.1</td>
<td>(4.2, 7.0)</td>
<td>4.8 ± 1.0</td>
</tr>
</tbody>
</table>

^a Findings from multivariate analysis of variance
^b Increased from initial to follow-up for all groups

DISCUSSION

This is the first investigation to examine the safety and effectiveness of a perturbation-based neuromuscular training program on dynamic balance in physically active adolescent females at risk of ACL injury. These results suggest that participation in the perturbation-based NM training program was safe but had no significant effect on YBT performance in either healthy or ACL-injured adolescent females. In healthy participants, a significant improvement in hip abduction strength was noted following completion of the perturbation-based NM training program; however, the improvement was not clinically significant. All other
the authors’ believe the results are generalizable to a representative population.

Previous investigations targeting physically active adult populations have demonstrated the effectiveness of perturbation-based NM training programs. Perturbation training has been used to eliminate an imbalance between quadriceps and hamstring performance in adult females and thus may be beneficial as an ACL injury prevention program for this demographic. Females with ACL-deficient knee also demonstrate improved gait and coordination after participating in a perturbation-based NM training program. Although these results are encouraging for ACL injury prevention and rehabilitation in an adult population, differences in lower extremity biomechanics observed during adolescence may place teenage females at greater risk of ACL injury. A recent meta-analysis reported an age-related association between the outcomes of neuromuscular training and the risk of ACL injury, and highlighted the value of neuromuscular training in female athletes under 18 years of age. This investigation was necessary to determine if the positive effects of perturbation-based NM training demonstrated in an adult population would also be observed in adolescent females at risk of ACL injury.

As all subjects randomized to the training group were able to complete the program without any incidence of knee joint pain, swelling or instability the current data suggest

Table 5. Proprioception and flexibility measurements for the healthy subjects, reported as mean ± SD, (95% confidence interval).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=12)</th>
<th>Perturbation (n=12)</th>
<th>p-valuea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Follow-up</td>
<td>Initial</td>
</tr>
<tr>
<td>Knee Proprioception (Δ⁰)</td>
<td>2.8 ± 1.2</td>
<td>3.3 ± 2.3</td>
<td>2.8 ± 1.7</td>
</tr>
<tr>
<td>(20.3, 3.6)</td>
<td>(18.4, 8.8)</td>
<td>(17.3, 3.9)</td>
<td>(13.5, 5.3)</td>
</tr>
<tr>
<td>Hip Flexibility (cm)</td>
<td>5.6 ± 15.6</td>
<td>7.1 ± 15.5</td>
<td>8.2 ± 7.1</td>
</tr>
<tr>
<td>(-4.3, 15.5)</td>
<td>(-2.7, 16.9)</td>
<td>(3.7, 12.7)</td>
<td>(18.13.4)</td>
</tr>
<tr>
<td>Ankle Flexibility (cm)</td>
<td>11.3 ± 3.5</td>
<td>11.0 ± 3.5</td>
<td>11.8 ± 3.2</td>
</tr>
<tr>
<td>(9.1, 13.5)</td>
<td>(8.8, 13.2)</td>
<td>(9.8, 13.8)</td>
<td>(10.3, 14.3)</td>
</tr>
</tbody>
</table>

a Findings from multivariate analysis of variance

Table 6. Proprioception and flexibility measurements for the ACL-injured subjects, reported as mean ± SD, (95% confidence interval).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=5)</th>
<th>Perturbation (n=5)</th>
<th>p-valuea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Follow-up</td>
<td>Initial</td>
</tr>
<tr>
<td>Knee Proprioception (Δ⁰)</td>
<td>3.6 ± 2.1</td>
<td>2.1 ± 1.5</td>
<td>1.9 ± 1.8</td>
</tr>
<tr>
<td>(1.0, 6.2)</td>
<td>(0.2, 4.0)</td>
<td>(-0.3, 4.1)</td>
<td>(-2.7, 9.3)</td>
</tr>
<tr>
<td>Hip Flexibility (cm)</td>
<td>1.1 ± 9.8</td>
<td>4.1 ± 7.6</td>
<td>9.5 ± 9.4</td>
</tr>
<tr>
<td>(-11.1, 13.3)</td>
<td>(-5.3, 13.5)</td>
<td>(-2.2, 21.2)</td>
<td>(18.18.2)</td>
</tr>
<tr>
<td>Ankle Flexibility (cm)</td>
<td>13.4 ± 3.3</td>
<td>13.3 ± 4.1</td>
<td>9.4 ± 1.8</td>
</tr>
<tr>
<td>(5.2, 21.6)</td>
<td>(8.2, 18.4)</td>
<td>(7.2, 11.6)</td>
<td>(7.6, 12.0)</td>
</tr>
</tbody>
</table>

a Findings from multivariate analysis of variance

measures of lower extremity strength, proprioception and flexibility were unaffected by completion of the training regime. The hypothesis that completion of a perturbation-based NM exercise program would improve YBT scoring, as well as lower extremity physical measures such as strength, proprioception and flexibility was not supported. While results suggest that the perturbation-based NM regime can be safely completed by both healthy and ACL-injured adolescent females, the results call into question the ability of the exercise program to successfully improve dynamic balance or other physical attributes believed to influence ACL-injury rates in this at-risk adolescent population.

The results of the current investigation address a gap in the current literature regarding the safety and effectiveness of perturbation-based NM training in at-risk adolescent females who regularly participate in recreational sporting activities. Previous research has established that YBT performance scores are significantly influenced by the sample population’s age, sex, sport involvement, and level of competitiveness. Beyond this, published studies on perturbation-based NM training have focused on a physically active adult population. The demographic and anthropometric data showed that the study sample was comprised of physically active females who participated in a variety of recreational sporting activities, have normal body weight and physical stature, and had reached or were approaching physical maturity. The participants were representative of an athletic adolescent female population at-risk for sustaining an ACL injury. As such, the authors’ believe the results are generalizable to a representative population.
that the perturbation-based training was safe. However, the data indicated that completion of the training program had no significant effect on the YBT reach distances of this adolescent female population. Previous studies reported improvements in YBT scores after healthy youth athletes completed NM training.21–25 Vitale et al. evaluated an eight-week program focused on core stability, plyometric and body-weight strengthening exercises21; two other studies assessed a four-week22 or 10-week25 FIFA 11+ Kids program which included seven activities: a running game, two jumping exercises, a balance/coordination task, two exercises targeting body stability and an exercise to improve falling technique. Recent meta-analyses suggest that combining plyometric and balance exercises may maximize effectiveness of preventive NM programs for healthy adolescent females.26,29,72 The present study used a perturbation-based NM program in isolation so both the preventive effects in healthy subjects and the rehabilitative effects in ACL-injured subjects could be assessed. The current results suggest that perturbation training alone did not affect dynamic balance. Notably, plyometric exercises used in other NM programs may not be safe or practical for ACL-injured subjects.73 Failla et al. found that the addition of a preoperative rehabilitation program that combined perturbation and strength training resulted in greater functional outcomes and return-to-sport rates two years after ACL reconstruction in an active adult population.13 Additionally, an investigation by Capin et al. concluded that there were no added benefits to including perturbation-based exercises to a post-operative RTS training program that incorporated strengthening, agility and plyometrics among young female athletes after ACL reconstruction.74 Thus, further investigations of perturbation-based training regimes with various parameters (such as longer duration or increased training intensity) and alternative forms of NM training that combine perturbation training with other exercises that are safe for ACL-injured adolescent females (such as resistance training, cardiovascular conditioning, core strengthening and gait re-education), are still necessary to improve prevention and rehabilitation programs for those at-risk.

LIMITATIONS

It is important to acknowledge that the current study had several limitations. First, this study utilized a YBT testing protocol that was established for use in an adult population. The typical YBT protocol in adults involves four training trials and three test trials to report a reach distance as the average of the three test trials.41 The few studies that have investigated YBT in an adolescent population have reported significant variations in the testing protocol.21–25,45 A recent study of the YBT in an adolescent male population noted a diminished reliability in adolescent athletes compared to adults and recommended that six practice trials and three test trials should be performed to increase the reliability of adolescent YBT assessments.61 Dynamic body changes that occur during the process of puberty may affect results and should to be accounted for to create a standardized YBT protocol specifically for the adolescent population. A second limitation is that the a priori analysis indicated that 22 subjects would provide adequate power to assess dynamic balance.58,59 Time and funding limits for study completion, as well as the strict age, gender, and activity-level inclusion criteria for participants in the ACL-injured group meant that recruitment was limited to only an exploratory group of 10 subjects. Having said this, the authors believe it was important to include this limited data set because pre-surgical data that is specific to an ACL-injured adolescent female population is lacking in the literature. Finally, the data collection methods focussed exclusively on quantitative outcome measures; however, many subjects commented on how participation in the perturbation-based NM training regime lead to subjective improvements in confidence levels when performing the follow-up testing and enhanced their ability to complete activities of daily living such as riding a bike or participating in physical education classes. The inclusion of subjective or psychological assessment tools would have expanded the analysis and allowed examination of how participation in the perturbation-based NM training program may have influenced participant’s confidence, self-esteem, and overall quality of life.

CONCLUSION

The goal of this study was to investigate the safety and effectiveness of a perturbation-based NM training program for improving dynamic balance in healthy and ACL-injured adolescent females. The results suggest that the perturbation training program is safe but has no significant effect on YBT performance in either the healthy or ACL-injured adolescent female participants. All measures of lower extremity strength, knee proprioception and flexibility of the hip and ankle joints were unaffected by the training program. Future research should examine whether perturbation-based NM training has a positive effect when combined with other forms of training currently used for ACL injury prevention or pre-operative rehabilitation in an at-risk population of adolescent female who regularly participate in sport.

CONFLICTS OF INTEREST

The Authors declare that there is no conflict of interest

Submitted: December 21, 2020 CDT, Accepted: March 18, 2021 CDT
REFERENCES


APPENDIX

### Perturbation Training Program Protocol

**Early Phase (Sessions 1-4)**

#### Treatment Goals:
- Expose athlete to perturbations in all directions
- Elicit an appropriate muscular response to applied perturbations (no rigid co-contraction)
- Minimize verbal cues

#### Movement Application:
- **Inform patient** of direction & timing
- Slow force; Low magnitude
- Each set 1 min

<table>
<thead>
<tr>
<th>Session</th>
<th>Rocker Board</th>
<th>Roller Board/Platform</th>
<th>Roller Board</th>
</tr>
</thead>
</table>
| 1       | Bilateral stance  
       | 2 sets anterior/posterior  
       | 2 sets medial/lateral | Bilateral stance  
       | 2 sets anterior/posterior  
       | 2 sets medial/lateral |
| 2       | Unilateral stance  
       | 2 sets anterior/posterior  
       | 2 sets medial/lateral | Unilateral stance  
       | 2 sets anterior/posterior  
       | 2 sets medial/lateral |
| 3       | Unilateral stance  
       | 3 sets anterior/posterior  
       | 3 sets medial/lateral | Unilateral stance  
       | 3 sets anterior/posterior  
       | 3 sets medial/lateral |
| 4       | Unilateral stance  
       | 3 sets anterior/posterior  
       | 3 sets medial/lateral | Unilateral stance  
       | 3 sets anterior/posterior  
       | 3 sets medial/lateral |
### Mid Phase (Sessions 5-7)

**Treatment Goals:**
- Add light sport-specific activity during perturbation techniques
- Improve athlete accuracy in matching muscle responses to perturbation intensity, direction and speed

**Movement Application:**
- **Unexpected forces**
- **Rapid, increasing magnitude** force application
- **Short delay** between subsequent force applications
- Begin combining **directional movement** of roller board
- **Distraction** via ball toss (Beginning at sessions 6)

<table>
<thead>
<tr>
<th>Session</th>
<th>Rocker Board</th>
<th>Roller Board/Platform</th>
<th>Roller Board</th>
</tr>
</thead>
</table>
| 5       | • Unilateral stance  
         | • 2 sets anterior/posterior  
         | • 2 sets medial/lateral        | • Unilateral stance  
         | • 1 set with injured limb on roller board, anterior/posterior  
         | • 1 set with uninjured limb on roller board, anterior/posterior  
         | • 1 set with injured limb on roller board, medial/lateral  
         | • 1 set with uninjured limb on roller board, medial/lateral  
         | • 2 sets with injured limb on roller board, combination movement  
         | • 2 sets with uninjured limb on roller board, combination movement  |
| 6       | • Unilateral stance  
         | • 2 sets anterior/posterior  
         | • 2 sets medial/lateral | • Unilateral stance  
         | • 1 set with injured limb on roller board, anterior/posterior  
         | • 1 set with uninjured limb on roller board, anterior/posterior  
         | • 1 set with injured limb on roller board, medial/lateral  
         | • 1 set with uninjured limb on roller board, medial/lateral  
         | • 2 sets with injured limb on roller board, combination movement  
         | • 2 sets with uninjured limb on roller board, combination movement  |
| 7       | • Unilateral stance  
         | • 2 sets anterior/posterior  
         | • 2 sets medial/lateral | • Unilateral stance  
         | • 1 set with injured limb on roller board, anterior/posterior  
         | • 1 set with uninjured limb on roller board, anterior/posterior  
         | • 1 set with injured limb on roller board, medial/lateral  
         | • 1 set with uninjured limb on roller board, medial/lateral  
         | • 3 sets with injured limb on roller board, combination movement  
         | • 3 sets with uninjured limb on roller board, combination movement  |
### Late Phase (Sessions 8-10)

**Treatment Goals:**
- Increase difficulty of perturbation by using sport-specific stances
- Obtain accurate, selective muscular responses to perturbations in any direction & any intensity, magnitude or speed

**Movement Application:**
- *Increased magnitude* force application
- *Random direction* movements
- Little to no delay between applications
- Distraction via ball toss

<table>
<thead>
<tr>
<th>Session</th>
<th>Roller Board</th>
<th>Roller Board/Platform</th>
<th>Roller Board</th>
</tr>
</thead>
</table>
| 8       | • Unilateral stance  
          • 1 set random (linear foot)  
          • 2 sets random (diagonal foot) | • 2 sets with injured limb on roller board, combination movement  
          • 2 sets with uninjured limb on roller board, combination movement  
          • 1 set with injured limb on roller board, combination movement (no delay)  
          • 1 set with uninjured limb on roller board, combination movement (no delay) | • Unilateral stance  
          • 2 sets combination movements  
          • 1 set combination movements (no delay) |
| 9       | • Unilateral stance  
          • 1 set random (linear foot)  
          • 2 sets random (diagonal foot) | • 3 sets with injured limb on roller board, combination movement (no delay)  
          • 3 sets with uninjured limb on roller board, combination movement (no delay) | • Unilateral stance  
          • 3 sets combination movements (no delay) |
| 10      | • Unilateral stance  
          • 1 set random (linear foot)  
          • 2 sets random (diagonal foot) | • 3 sets with injured limb on roller board, combination movement (no delay)  
          • 3 sets with uninjured limb on roller board, combination movement (no delay) | • Unilateral stance  
          • 3 sets combination movements (no delay) |
BACKGROUND
The Functional Movement Screen™ (FMS™) is a clinical instrument designed to use movement behaviors to screen individuals for injury risk. Current rater certification programs focus on extensive, individualized training, which may not be appropriate in all screening contexts.

PURPOSE
The purpose of this research was to examine the effect of a two-hour FMS™ training seminar on measures of reliability between previously untrained scorers.

STUDY DESIGN
Repeated measures, descriptive cohort study.

METHODS
Four novice raters completed a two-hour training course administered by an FMS™-certified, licensed physical therapist. The novices and the instructor then scored a group of 16 individuals on the seven FMS™ component tests on two separate occasions. Interrater reliability was assessed for FMS™ component scores using Fleiss' kappa and Krippendorff's $\alpha$. Interrater reliability for the FMS™ composite score was assessed using a two-way ICC for agreement (a priori significance level=0.05).

RESULTS
Reliability ranged from fair to almost perfect (kappa) for Deep Squat (0.61 Day 1, 0.79 Day 2), Shoulder Mobility (0.90 Day 1, 1.00 Day 2), Active Straight Leg Raise (0.53 Day 1, 0.69 Day 2), and Trunk Stability Push Up (0.48 Day 1, 0.49 Day 2) on both testing occurrences (p<0.05). Reliability (kappa) was fair for Inline Lunge (0.24 Day 1, 0.39 Day 2) and poor for Hurdle Step (Day 1 -0.01, Day 2 no result) and Rotary Stability (Day 1 -0.03, Day 2 -0.01). Results for Krippendorff’s $\alpha$ were similar, with unacceptable interrater reliability for Hurdle Step (Day 1 -0.01, Day 2 1.00), Inline Lunge (Day 1 0.31, Day 2 0.39), and Rotary Stability (Day 1 -0.02, Day 2 -0.01). Interrater composite score reliability (ICC) was good (0.79 Day 1, 0.84 Day 2; both p<0.05).

CONCLUSIONS
Findings suggest that a brief training seminar may be sufficient to ensure acceptable reliability in many, but not all, of the FMS™ component tests and composite score.
**Levels of Evidence**

**Level 2b**

**BACKGROUND**

The toll of musculoskeletal injuries is difficult to quantify, but is likely substantial among nations across the economic spectrum. The ramifications of musculoskeletal injury are far-reaching and include costs related to healthcare as well as impact on quality of life, future health, and workplace productivity, to name a few. Physical activity, despite its readily apparent benefits to physical health, increases one’s exposure to potentially injurious events and is often implicated in initiating the cycle of injury-related personal and societal costs. Recent epidemiological studies of sport-related injury in the U.S. estimate 8.6 million Americans report an activity-related injury each year. Preserving the benefits of physical activity while avoiding adverse outcomes requires a balance between participation and, where possible, minimizing exposure.

One potential method for reducing such exposures involves screening for or modifying high-risk movement behaviors. The developers of the FMS™ proposed that the practice of sports medicine was lacking with respect to injury risk screening. They describe a gap between 1) the pre-participation medical clearance exam, and 2) performance testing designed to guide sport-related training or tactical decisions. Their solution, which has since gained considerable traction, involves the screening of fundamental movement behaviors as an indicator of potential activity-related injury risk and as an initial means of identifying possible avenues of remediation.

Initial research on the FMS™ indicated that it may help prospectively discriminate individuals at high vs. low risk for activity-related injury on the basis of a standardized movement assessment battery. This observation has led to an increased focus on the application of movement screens, both as a predictor of risk and to support the design of training programs. Additional movement assessment instruments developed to date have sought to address a range of populations and specific activity-based needs. These developments, and the accelerating pace of research on the topic of movement quality, attest to the continued interest in applying such instruments clinically.

Notwithstanding, the proliferation of movement screens as a pre-participation tool has led to a concomitant increase in the demand for raters and the lack of demonstrated competence with visual observation when evaluating movement. As the scale of application increases for the FMS™ and similar clinical instruments, there is a potential for their reliability to suffer within and across studies. This may stem from variability in rater expertise, individual raters adopting personal preferences in rating style, or the mutual influence of different screening systems featuring similar component tests. Any such source of error has the potential to affect clinical and scientific interpretation of the associated rating systems. Alternatively, one may increase confidence in their meaning to the extent such sources of error can be addressed. A feasible method of calibrating clinical movement assessments (or the raters who rate them) may help ensure data quality and insulate these instruments from reliability concerns associated with scale of application.

Assessing practical methods by which raters with varying levels of experience as a movement professional—and varying levels of exposure to specific movement assessment instruments—can achieve greater reliability in applying movement quality assessments. This may be particularly useful in high-volume settings, in which effects related to rater variation have a greater likelihood of obscuring meaningful trends.

The subject of FMS™ reliability among raters of varying experience has been partially addressed by previous work. While specific findings vary by study, authors appear to conclude more often than not that the instrument is reliable for the purposes investigated. Even so, valid concerns have been raised about the conclusiveness of the research.

**METHODS**

**EXPERIMENTAL APPROACH TO THE PROBLEM**

Component (i.e., item) and composite FMS™ scores were acquired on two occasions from a group of five raters. The raters consisted of four novice second-year physical therapy students with no prior FMS™ training or experience, and one expert who was FMS™ certified with three years’ experience using FMS™ and has been a licensed physical therapist for 20 years. The novice raters participated in a two-hour training seminar provided by the expert rater eight days prior to the initiation of data collection. The training session consisted of initially viewing each of the seven screening tests, totaling approximately 75 minutes, of the FMS™ scoring video (Functional Movement Systems). Ad-
ditionally, the seven movement patterns, three clearing tests, examiner verbal instructions, and scoring criteria were explained in detail by the expert rater. Summary sheets for each FMS™ movement were provided to the raters, including written and visual descriptions of scoring from zero to three for each movement pattern. Novice raters then performed, practiced, and scored each of the seven movement patterns and three clearing tests.

A sample of 16 subjects was scored twice by each rater with four days between each session. On both occasions, a researcher read the scripted instructions used the same materials as used in the training session to have the subjects perform each test. The tests were scored in real-time by all raters simultaneously and subsequently analyzed to establish reliability.

SUBJECTS

A total of sixteen subjects (12 females [23.33 ± 1.61 years, 164.68 ± 5.94 cm, 61.97 ± 9.33 kg] and four males [23.75 ± 1.71 years, 181.61 ± 10.47 cm, 88.22 ± 20.18 kg]) participated in this study. Participation was open to healthy adults without restrictions to physical activity. Prior to participation, subjects signed an informed consent form approved by the university Institutional Review Board.

PROCEDURES

Participants reported to the testing site on Day 1 of testing, and returned to repeat the test four days later (Day 2) at the same location. Upon arrival, participants were instructed in the performance of each movement pattern in the order specified by Cook et al.4,5 The standardized order of movement patterns and tests was as follows: 1) Deep Squat (DS), 2) Hurdle Step (HS), 3) Inline Lunge (ILL), 4) Shoulder Mobility (SM), 5) Shoulder Clearing Tests, 6) Active Straight Leg Raise (ASLR), 7) Trunk Stability Push Up (TSPU), 8) Spinal Extension Clearing Test, 9) Rotary Stability (RS) (prior to changes of 2020), 10) Spinal Flexion Clearing Test. Test order and verbal instructions were scripted for criteria to meet scores of “grade 3” or “grade 2” and each subject completed each test position regardless of rater’s score. All raters observed and scored the same subject at the same time. Raters were permitted to move about the testing room and to request that participants perform additional repetitions of any test, but were not permitted to discuss scores. These same procedures were repeated four days later. Participants were instructed not to practice the test behaviors between the first and second testing occasions. Summary sheets for each FMS™ movement were provided, including written and visual descriptions of scoring for each movement pattern. Novice raters performed, practiced, and scored each of the seven movement patterns and three clearing tests. Prior to data collection, interrater reliability for novice raters for the DS, HS, and ILL movement patterns was rated and found to have excellent reliability after viewing and scoring video clips of these three movement patterns. These three movement patterns were selected by the researchers due to the increased complexity of the grading criteria for those movement patterns when compared to the other movement patterns.

Each item was rated by all participants in real-time based on the originally published scoring criteria as instructed during the training seminar. Raters were additionally instructed to record the lower of two scores as the component score for any test in which a bilateral asymmetry was noted, and to assign a component score of 0 in any test which pain was reported or if an associated clearing test was positive (i.e. evoked pain).

STATISTICAL ANALYSES

Interrater reliability was analyzed separately for each Day 1 component score and also for the Day 1 composite score, the latter of which is simply a sum of the component scores. To account for the number of raters (n = 2) and the structure of the component data, Krippendorff’s α and Fleiss’ Kappa were computed. Note, Krippendorff’s α is designed for ordinal data whereas Fleiss’ kappa is designed for categorical data. To facilitate comparison with previously published data intraclass correlation coefficients (ICC) was computed for each component score, although, it should be noted, that ICC may not be appropriate for ordinal data. For the composite score, interrater reliability was assessed using ICC. All ICC coefficients were calculated using two-way ICC models for agreement. Interrater reliability for Day 2 scores was calculated separately using the same methods described for Day 1. All statistical analyses were conducted using R version 3.6.1 (the R Foundation; Vienna, Austria) at an a priori significance level of α = 0.05. Coefficients were interpreted in accordance with published guidelines.17,18

Specifically, ICC was interpreted as poor (0.00 – 0.40), fair/good (0.40 – 0.75), excellent (0.75 – 1.00). Krippendorff’s α was interpreted as unacceptable, (0.00 – 0.65), tentatively acceptable (0.65 – 0.80), or acceptable (0.80 – 1.00). Finally, Fleiss’ Kappa was interpreted as slight (0.00 – 0.20), fair (0.21 – 0.40), moderate (0.41 – 0.60), substantial (0.61 – 0.80), or almost perfect (0.81 – 1.00).

RESULTS

Score counts for each combination of Rater * Day * Test Item are shown in Table 1. Interrater reliability on Day 1 and Day 2 are summarized in Tables 2 and 3, respectively. The results vary considerably depending on the statistical test that was utilized. Interpreting Krippendorf’s α, Day 1 interrater reliability was unacceptable for Hurdle Step, Inline Lunge, Active Straight Leg Raise, and Rotary Stability; tentatively acceptable for Deep Squat; and acceptable for Shoulder Mobility. Based on Fleiss’ Kappa, Day 1 interrater reliability was poor for Hurdle Step and Rotary Stability (p > 0.05); fair for Inline Lunge and Trunk Stability Push Up; moderate for Active Straight Leg Raise; substantial for Deep Squat; and almost perfect for Shoulder Mobility. Day 1 ICCs indicated poor interrater reliability for Hurdle Step (p > 0.05), Rotary Stability (p > 0.05), and Inline Lunge; fair/good interrater reliability for Active Straight Leg Raise, and Trunk Stability Push Up; and excellent reliability for Deep Squat and Shoulder Mobility.
## Table 1. FMS™ item score tallies by rater for each day.

<table>
<thead>
<tr>
<th>Score</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>R1</td>
<td>R2</td>
<td>R3</td>
<td>R4</td>
</tr>
<tr>
<td><strong>Day 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>DS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ILL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SM</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ASLR</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TSPU</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| **Day 2** |
| DS    | 0  | 0  | 0  | 0  | 0  | 3  | 3  | 3  | 3  | 6  | 11 | 10 | 10 | 10 | 8  |
| HS    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 16 | 16 | 16 | 16 | 16 |
| ILL   | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 13 | 10 | 11 | 13 | 15 |
| SM    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 4  | 4  | 4  | 4  | 4  |
| ASLR  | 0  | 0  | 0  | 0  | 0  | 5  | 4  | 4  | 4  | 3  | 5  | 5  | 6  | 6  | 4  |
| TSPU  | 0  | 0  | 0  | 0  | 0  | 9  | 7  | 5  | 7  | 9  | 6  | 8  | 4  | 7  | 6  |
| RS    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 16 | 16 | 15 | 16 | 16 |

Raters R1-R4 are the novice raters. RS is the expert rater. DS = Deep Squat; HS = Hurdle Step; ILL = Inline Lunge; SM = Shoulder Mobility; ASLR = Active Straight Leg Raise; TSPU = Trunk Stability Push Up; RS = Rotary Stability.
Table 2. Interrater reliability statistics for Day 1 FMS™ item scores.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Coefficient</th>
<th>Statistic</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>0.75</td>
<td>$F_{(15, 60)} = 16.96$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>HS</td>
<td>0.00</td>
<td>$F_{(15, 60)} = 1.00$</td>
<td>0.467</td>
</tr>
<tr>
<td>ILL</td>
<td>0.32</td>
<td>$F_{(15, 62)} = 3.58$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>SM</td>
<td>0.96</td>
<td>$F_{(15, 60)} = 138.14$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>ASLR</td>
<td>0.68</td>
<td>$F_{(15, 38)} = 14.95$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>TSPU</td>
<td>0.68</td>
<td>$F_{(15, 32)} = 15.42$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>RS</td>
<td>-0.02</td>
<td>$F_{(15, 59)} = 0.92$</td>
<td>0.549</td>
</tr>
<tr>
<td><strong>Krippendorff’s α</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>0.74</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>HS</td>
<td>-0.01</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ILL</td>
<td>0.31</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>SM</td>
<td>0.91</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ASLR</td>
<td>0.64</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>TSPU</td>
<td>0.68</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>RS</td>
<td>-0.02</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Fleiss’ Kappa</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>0.61</td>
<td>$z = 10.51$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>HS</td>
<td>-0.01</td>
<td>$z = -0.16$</td>
<td>0.873</td>
</tr>
<tr>
<td>ILL</td>
<td>0.24</td>
<td>$z = 3.38$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>SM</td>
<td>0.90</td>
<td>$z = 13.47$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>ASLR</td>
<td>0.53</td>
<td>$z = 8.95$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>TSPU</td>
<td>0.48</td>
<td>$z = 8.88$</td>
<td>&lt;0.01*</td>
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<tr>
<td>RS</td>
<td>-0.03</td>
<td>$z = -0.32$</td>
<td>0.746</td>
</tr>
</tbody>
</table>

DS = Deep Squat; HS = Hurdle Step; ILL = Inline Lunge; SM = Shoulder Mobility; ASLR = Active Straight Leg Raise; TSPU = Trunk Stability Push Up; RS = Rotary Stability.

Interpreting Krippendorff’s α for Day 2, interrater reliability was acceptable for Deep Squat, Hurdle Step, Shoulder Mobility, and Active Straight Leg Raise; tentatively acceptable reliability for Inline Lunge and Rotary Stability. Fleiss’ kappa indicated poor agreement for Rotary Stability (p > 0.05); fair agreement for Inline Lunge; moderate agreement for Trunk Stability Push Up; substantial agreement for Deep Squat and Active Straight Leg Raise; and almost perfect agreement for Shoulder Mobility. Day 2 ICCs indicated poor interrater reliability for Rotary Stability (p > 0.05); fair/good interrater reliability for Inline Lunge and Trunk Stability Push Up; and excellent interrater reliability for Deep Squat, Shoulder Mobility, and Active Straight Leg Raise. Day 2 interrater ICC for Hurdle Step could not be calculated.

Finally, interrater ICC for the composite score was excellent on both days (Day 1 ICC = 0.79, Day 2 ICC = 0.84; Table 4). Intraclass correlation coefficients (two-way models for agreement) calculated separately for Day 1 and Day 2 FMS™ composite scores.

**DISCUSSION**

The results of this study indicate that interrater FMS™ item score reliability was variable following a standardized two-hour training seminar in raters previously unfamiliar with the FMS™. We elaborate on specific FMS™ components in the following paragraphs. Additionally, we observed that interrater reliability of the composite score was excellent. One caveat that bears mentioning before further discussion is the lack of variability within certain component ratings. Specifically, nearly all raters assigned a score of "2" for every participant—on both days—in the Hurdle Step and Rotary Stability tests. Depending on the statistical test, this may result in a finding that agreement between raters is either essentially perfect or cannot be calculated. Whichever the case, these models should be interpreted with caution.

Results concerning the composite score are fairly consistent with previous findings. For example, Onate et al. observed an interrater ICC of 0.98 for the FMS™ composite score, and Smith et al. observed interrater ICCs of 0.87 and 0.89, respectively, on two separate days of testing. The authors conclude that the composite score can be rated reliably by judges of varying levels of experience. While this observation does strengthen the case for composite scor-
Table 3. Interrater reliability statistics for Day 2 FMS™ item scores.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Coefficient</th>
<th>Statistic</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC</td>
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</tr>
<tr>
<td>DS</td>
<td>0.86</td>
<td>$F_{(15, 47)} = 38.02$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>HS</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ILL</td>
<td>0.42</td>
<td>$F_{(15, 61)} = 4.89$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>SM</td>
<td>1.00</td>
<td>$F_{(15, 59)} = 1000$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>ASLR</td>
<td>0.85</td>
<td>$F_{(15, 58)} = 32.99$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>TSPU</td>
<td>0.68</td>
<td>$F_{(15, 25)} = 17.26$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>RS</td>
<td>0.00</td>
<td>$F_{(15, 60)} = 1.00$</td>
<td>0.467</td>
</tr>
<tr>
<td>Krippendorff’s $\alpha$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>0.85</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>HS</td>
<td>1.00</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ILL</td>
<td>0.39</td>
<td>--</td>
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<tr>
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</tr>
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<td>--</td>
<td>--</td>
</tr>
<tr>
<td>RS</td>
<td>-0.01</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Fleiss’ Kappa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>0.79</td>
<td>$z = 13.53$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>HS</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ILL</td>
<td>0.39</td>
<td>$z = 4.94$</td>
<td>&lt;0.01*</td>
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<tr>
<td>SM</td>
<td>1.00</td>
<td>$z = 12.65$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>ASLR</td>
<td>0.69</td>
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<td>&lt;0.01*</td>
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<tr>
<td>TSPU</td>
<td>0.49</td>
<td>$z = 8.21$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>RS</td>
<td>-0.01</td>
<td>$z = -0.16$</td>
<td>0.873</td>
</tr>
</tbody>
</table>

DS = Deep Squat; HS = Hurdle Step; ILL = Inline Lunge; SM = Shoulder Mobility; ASLR = Active Straight Leg Raise; TSPU = Trunk Stability Push Up; RS = Rotary Stability.

Table 4. Interrater reliability for Day 1 and Day 2

<table>
<thead>
<tr>
<th>Outcome</th>
<th>ICC</th>
<th>Statistic</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>0.79</td>
<td>$F_{(15,59)} = 21.52$</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Day 2</td>
<td>0.84</td>
<td>$F_{(15,40.1)} = 34.84$</td>
<td>&lt;0.01*</td>
</tr>
</tbody>
</table>

Intraclass correlation coefficients (two-way models for agreement) calculated separately for Day 1 and Day 2 FMS™ composite scores.

In contrast, FMS™ item/component scores present a more granular perspective of movement quality and may be less vulnerable to criticism concerning their psychometric qualities. The study’s findings for Rotary Stability were again consistent with Onate et al., who observed that a kappa statistic could not be calculated due to lack of variability. This study’s remaining results show a pattern of interrater agreement that is more or less similar to that of Onate et al. for the item scores, albeit a lower coefficient in all cases except Shoulder Mobility. This may be due in part to the use of Fleiss’ kappa where Onate et al. used Cohen’s kappa. (The latter was not an option in this study design because of the number of raters involved.) Minick et al.23 also used a two-rater kappa and reported generally higher agreement than this study found. Particularly noteworthy in their findings were considerably higher levels of observed agreement for Hurdle Step and Rotary Stability. Shultz et al.18 evaluated interrater reliability of FMS™ item scores using Krippendorff’s $\alpha$ and found unacceptable agreement in all cases except Hurdle Step, for which agreement was in the “acceptable” range. This may be partially attributable to the study population (DI varsity athletes), but does stand in...
The clinical interpretation of agreement depends on the choice of reliability statistic. This study endeavored to make the case that ICC should not be used for assessing reliability of ordinally scaled items such as the FMS™ component scores. In those cases, kappa (Fleiss or Cohen) and Krippendorff’s $\kappa$ are better suited models. In the dataset for this study, Active Straight Leg Raise and Trunk Stability Push Up—along with the Deep Squat, to a lesser extent—are perhaps the best examples of how ICC results may give the impression of an unrealistically high level of reliability. However, ambiguity of interpretation remains even when comparing results from kappa and $\kappa$ models. For instance, where Active Straight Leg Raise and Inline Lunge are considered "unacceptable" by $\kappa$ standards, the authors of this study would judge them as having moderate and fair agreement, respectively, based on their kappa models (referring to Day 1 results).

Based on the combined results for this study, the best candidates for inclusion in a high-volume screening effort following a brief, introductory training seminar would be: Shoulder Mobility, Active Straight Leg Raise, Deep Squat, and Trunk Stability Push Up. With one exception, each of these FMS™ components achieves a level of reliability that could be considered at least "moderate" (kappa) or "tentatively acceptable" ($\kappa$) on both days. Active Straight Leg Raise, the exception, misses the $\alpha$ cutoff for being considered "tentatively acceptable" on Day 1 by a slim margin. These findings could be useful for those planning large-scale screens. Further, they might suggest a refinement of scoring criteria to the less reliable items or, at least, more focused training prior to their use.

Before concluding, this study highlights one potentially telling observation. The interrater reliability models feature five raters, one of whom was designated an "expert" and the rest "novices". The rater designations are not accounted for in the models, but are specified in the Table 1 caption. In several cases, it appears that the cluster of novice raters disagrees systematically with the expert (e.g., DS, ILL). For example, the expert rater assigned a Deep Squat score of 1 to six subjects on both Day 1 and Day 2. In contrast, only two or three subjects were assigned a Deep Squat score of 1 by the novice raters. The expert rater also stands alone in assigning more 2’s and fewer 3’s on the Inline Lunge (both days) when compared with the novices, the latter of whom agree more closely with each other than they do with the expert. These systematic biases existed despite checking for interrater reliability on DS, HS, and ILL during the training session. It may represent opportunities to firm up reliability by modifying the training method, such as using live subjects rather than video, and by devoting additional training such that consensus is achieved with the criterion rater prior to data collection.

LIMITATIONS

There are several limitations in the current study. First, scoring by all raters was performed in real-time. While this better simulates the conditions under which the FMS™ would be administered, simultaneous assessment by five raters may have affected scores by virtue of requiring raters to view test subjects from different vantage points. This may be especially true for multidimensional tests such as the Inline Lunge, for which scores are likely to be more sensitive to viewing angle. The second limitation concerns the test subjects themselves. These individuals comprised a limited (n = 16) convenience sample of graduate students. Third, subjects may have scored differently from day 1 to day 2; however, the test subjects were blinded to their scores. Although raters may have recalled scores from Day 1, biasing their Day 2 scores, it is unlikely due to the number of scripted movement patterns tested and since re-testing was four days later. As such, our findings should be considered preliminary pending further work involving diverse samples with a greater number of observations.

CONCLUSIONS

A two-hour training session on the scoring and administration of the Functional Movement Screen™ in previously untrained raters produced acceptable interrater reliability in the Shoulder Mobility, Active Straight Leg Raise, Deep Squat, and Trunk Stability Push Up tests. Based on the results of the current study, the authors are not able to conclude that the remaining tests—Hurdle Step, Rotary Stability, and Inline Lunge—are comparably reliable after similar training. A brief training seminar could be used prior to high-volume movement screens to provide reliable measurements involving multiple raters, particularly where rater experience is limited.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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Background
Functional balance training is crucial for both rehabilitation and prevention. A Dynamic Innovative Balance System (DIBA) is readily available for utilization in both functional and postural control training in a wide variety of dynamic conditions.

Purpose
The purpose of this study was to compare the effectiveness of the DIBA and standard balance training tools on dynamic and static balance.

Study Design
Randomized controlled trial

Methods
Thirty-six healthy males (18 to 32 years) were randomly assigned to group DIBA (n=18) or to the control group (n=18) who performed balance training using a balance board, a wobble board, the BOSU, or a soft cushion block for eight weeks. Each participant was assessed before training, at the end of the fourth and eighth week by using the Flamingo balance test (FBT) for assessing static balance ability and using Y-Balance Test (YBT) for dynamic balance ability.

Results
No significant differences were found in FBT and YBT between the DIBA and control groups at the end of fourth week (p>0.05). However, at the end of the eighth week, the DIBA group demonstrated statistically significantly better balance ability on the anterior component of YBT (p=0.001) and FBT (p=0.024) than controls.

Conclusion
The results of this study suggest that the DIBA was effective in both static and dynamic balance training and it may be used alongside other balance tools in a clinical setting. Further studies should include in lower extremity problems to confirm that DIBA training adaptations are transferred to clinical improvements in performance and balance qualities.

Level of Evidence
2d
INTRODUCTION

In the last decade, several balance systems have been used for functional training in balance and postural control during rehabilitation and return to sports. Accurate control of posture and balance depends on a correct motor command, which in turn relies on vestibular, visual, and proprioceptive inputs. Balance and functional exercise interventions are essential parts of a rehabilitation program to improve balance and kinesthetic sense of body parts in order to prevent injury recurrence. Most of current balance training systems provide training over a static foot, placed on different surfaces. According to published literature, the BOSU, wobble board, rocker board, and virtual reality systems like Nintendo Wii are used for functional balance training. However, patients may have avoided putting the necessary body weight on the injured leg during bilateral stance while using such systems during the training program. This reduces the motivation of a patient because they may fear re-injury or aggravation of their pain. Despite many balance training systems having been described in the literature, few provide dynamic training options and promote sufficient weight shift to the injured side.

The Dynamic Innovative Balance (DIBA) system consists of two mobile foot platforms that independently move in antero-posterior and medio-lateral directions. This mechanism is provided with a remote control, which gives advantages for control of the device for change(s) of direction. This system allows the imitation of movements that occur during functional daily activities. The subject being trained places his/her feet on the platforms and attempts to maintain his/her balance in different positions such as standing, walking, squatting, and lunging on the moving foot platforms in pre-determined directions. Balance training exercises are selected among a series of exercise and training protocols, which have been developed for use with the DIBA.

To the authors’ knowledge, there is no published literature examining any balance exercise or training protocols with the DIBA in clinical settings. Therefore, the purpose of this study was to compare the effectiveness of the DIBA and standard balance training tools on dynamic and static balance. It was hypothesized that balance exercises and training with DIBA as effective as exercising with standard balance tools.

METHODS

PARTICIPANTS

A total of 36 healthy males with age ranging between 18-32 years participated in this study. Participants were randomly assigned into two groups as DIBA group (n=18) and control group (n=18). For allocation of the participants, a computer-generated list of random numbers was used. The University Institutional Review Board approved the ethical protocol for this study, and all volunteers were informed about the nature of the study and signed a written consent form. Flow chart of the study is shown in Figure 2.

Inclusion criteria included: males, age 18-40yrs, with no lower extremity injury in the prior six months, no chronic pain or surgery in lower extremity, right lower extremity dominant, and willing to participate to the study as a volunteer. Participants who had any neuromuscular, cardiorespiratory, or musculoskeletal condition were excluded from the study. The study was single blind.
piratory, neurologic disorders, had sustained any musculoskeletal injuries over the prior six months, were currently experiencing pain anywhere in the body, and had not participated in three training sessions or two assessment sessions, or had pain that could interfere with the training and assessment sessions were excluded from this study. The participants were also advised not to consume alcohol, take nutritional supplements, participate in physical activities, or use other recovery techniques such as analgesic drugs and cryotherapy, throughout this study. Moreover, they were asked to maintain their usual nutritional and water intake over the course of this study. Participants, who met inclusion criteria were randomly chosen among initially assessed 48 healthy males, who performed moderate intensity exercise lasting from 30 to 60 minutes at least three days a week based on the criteria of American College of Sport Medicine.\textsuperscript{13,14}

**PROCEDURE**

**Balance assessment:** Both the DIBA and control groups were assessed before balance training, and again at the end of the 4\textsuperscript{th} and 8\textsuperscript{th} weeks. The Y-Balance test (YBT) was employed for dynamic balance assessment and Flamingo balance test (FBT) was used for static balance assessment as described elsewhere.\textsuperscript{15,16} Each test was repeated three times consecutively using the dominant lower extremity (all participants were right-side dominant), and the average value of three measurements was used for statistical analysis.

The DIBA uses an electromechanical dynamic balance training system, which developed by the authors. It consists of two-foot platforms that move on its rail. The rails also are able to move mediolaterally to increase or decrease distance between the feet for changing exercise and training load.

**Balance training program:** All participants performed balance training supervised by same physical therapist at the same clinic. Each training session was set 45-60 minutes, three days per week for eight weeks in total. Although, both groups received different types of exercise, the intensity of exercises for the DIBA group were divided into three categories according to their intensity. The low intensity exercises were completed during the first two weeks, moderate intensity exercises in the 3\textsuperscript{rd} to 4\textsuperscript{th} weeks, and high intensity exercises were completed during the 5\textsuperscript{th} to 8\textsuperscript{th} weeks. Balance sample exercises for the DIBA are shown in Figure 1.

Duration, repetitions and number of sets are given Table 1.

**Exercise protocol for control group:** Participants in the control group were received common balance exercises using BOSU, balance boards, wobble board, and a soft cushion block. Exercise duration was 45-60 minutes, three days per week for eight weeks in total.

**STATISTICAL METHODS**

Data were analyzed using IBM SPSS v.22 (IBM, Chicago, IL, USA). Schapiro Wilk test was employed for whether data were normally distributed. As data were not normally distributed, Mann Whitney U test was used for between group comparisons, and Wilcoxon Signed Rank test with Bonfer-

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**Figure 2. Flow diagram of randomized controlled trial.**

DIBA= Dynamic Innovative Balance System.

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The demographic data is shown in Table 2. Both the groups were not statistically significantly different in age, body weight, body height, and body mass index (p>0.05).

There were no significant differences between groups in scores on the components of the YBT (p>0.05) at baseline and at the end of 4\textsuperscript{th} week measurements. However, a statistically significant difference was seen for only anterior component of YBT (p=0.001) in favor of the DIBA group at the end of the 8\textsuperscript{th} week. Within group comparisons demonstrated significantly higher YBT scores in the anterior (p=0.01) and postero-medial (p=0.014) directions at the end of 8\textsuperscript{th} week compared with baseline scores for the DIBA group (Figure 3). Similarly, the scores of postero-medial (p=0.008) and postero-lateral (0.001) components of the YBT were significantly higher at the end of 8\textsuperscript{th} week compared with those of baseline measurement for control group (Table 3).

There was not a statistically significant difference between groups in scores of the FBT at baseline and at the end of 4\textsuperscript{th} week (p>0.05); however, the number of falls was significantly lower in favor of the DIBA group (p=0.024) at the end of the 8\textsuperscript{th} week. The DIBA group demonstrated a statistically significant lower number of falls during FBT at the end of 8\textsuperscript{th} week (p=0.011) compared to those at baseline measurement. There was not a statistically significant difference within group FBT scores (p=0.0167; Bonferroni correction) in control group (Figure 4).

**DISCUSSION**

The purpose of this study was to investigate whether results
Table 1. Duration, repetitions and number of sets in balance exercises for DIBA and Control Group*

<table>
<thead>
<tr>
<th>Weeks</th>
<th>Balance Training Program</th>
<th>DIBA group Time X repetition</th>
<th>Control group Time X repetition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2 weeks</td>
<td>1: Steady standing in upright position *</td>
<td>60s X 8 rep.</td>
<td>60s X 8 rep.</td>
</tr>
<tr>
<td></td>
<td>2: Steady standing in upright position on DIBA with balance</td>
<td>60s X 8 rep.</td>
<td>60s X 8 rep.</td>
</tr>
<tr>
<td></td>
<td>3: Steady standing in the squat position *</td>
<td>30s X 10 rep.</td>
<td>30s X 10 rep.</td>
</tr>
<tr>
<td></td>
<td>4: Steady standing in the squat position on DIBA</td>
<td>30s X 10 rep.</td>
<td>30s X 10 rep.</td>
</tr>
<tr>
<td></td>
<td>5: Squatting exercise in lunge position *</td>
<td>10 rep. X 3 set</td>
<td>10 rep. X 3 set</td>
</tr>
<tr>
<td></td>
<td>6: Squatting exercise in lunge position on DIBA</td>
<td>10 rep. X 3 set</td>
<td>10 rep. X 3 set</td>
</tr>
<tr>
<td>3-4 weeks</td>
<td>7: Catching and throwing ball in steady lunge position on DIBA and on floor *</td>
<td>15 rep. X 3 set</td>
<td>15 rep. X 3 set</td>
</tr>
<tr>
<td></td>
<td>8: Catching and throwing ball in steady squat position on DIBA and on floor *</td>
<td>30s X 10 rep.</td>
<td>30s X 10 rep.</td>
</tr>
<tr>
<td></td>
<td>9: Steady standing in upright position while DIBA foot platforms move away and toward each other.</td>
<td>12 rep. X 3 set</td>
<td>12 rep. X 3 set</td>
</tr>
<tr>
<td></td>
<td>10: Squatting exercise as DIBA foot platforms move away from and toward each other.</td>
<td>12 rep. X 3 set</td>
<td>12 rep. X 3 set</td>
</tr>
<tr>
<td></td>
<td>11: Steady standing in squat position with eyes closed on DIBA and on floor*</td>
<td>30s X 10 rep.</td>
<td>30s X 10 rep.</td>
</tr>
<tr>
<td></td>
<td>12: Steady standing in lunge position with eyes closed. on DIBA and on floor*</td>
<td>30s X 10 rep.</td>
<td>30s X 10 rep.</td>
</tr>
<tr>
<td>5-8 weeks</td>
<td>13: Rotation of upper body as foot platforms move away from and toward each other on DIBA and on floor *</td>
<td>All direction 8 repX3set</td>
<td>All direction 8 repX3set</td>
</tr>
<tr>
<td></td>
<td>14: Lunge exercise as foot platforms move antero-posteriorly while they away from each other and on floor *</td>
<td>15 rep.X 3 set</td>
<td>15 rep.X 3 set</td>
</tr>
<tr>
<td></td>
<td>15: Single leg stances foot platforms move away from and toward each other and antero-posteriorly on floor *</td>
<td>30s X 12 rep.</td>
<td>30s X 12 rep.</td>
</tr>
<tr>
<td></td>
<td>16: Catching a ball during single leg stance on foot platforms as move away from and toward each other and antero-posteriorly on floor *</td>
<td>30s X 12 rep.</td>
<td>30s X 12 rep.</td>
</tr>
<tr>
<td></td>
<td>17: Single leg stance with eyes open as foot platforms move away from and toward each other and antero-posteriorly on floor *</td>
<td>20s X 8 rep.</td>
<td>20s X 8 rep.</td>
</tr>
<tr>
<td></td>
<td>18: Single leg stance with eyes closed as foot platforms move away from and toward each other and antero-posteriorly on floor *</td>
<td>20s X 8 rep.</td>
<td>20s X 8 rep.</td>
</tr>
</tbody>
</table>

s: second; Rep: repetition; *= exercises performed by the control group

Table 2. Demographic characteristics of the subjects

<table>
<thead>
<tr>
<th></th>
<th>DIBA group (n=18) Mean±SD (Range)</th>
<th>Control group (n=18) Mean±SD (Range)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (year)</td>
<td>24.4±3.3 (18-32)</td>
<td>23.7±2.8 (20-29)</td>
<td>0.525</td>
</tr>
<tr>
<td>Body Height (cm)</td>
<td>178.2±5.0 (168-188)</td>
<td>176.1±5.7 (169-176)</td>
<td>0.253</td>
</tr>
<tr>
<td>Body Weight (kg)</td>
<td>73.2±6.9 (62-85)</td>
<td>70.8±6.7 (58-82)</td>
<td>0.314</td>
</tr>
<tr>
<td>Body Mass Index (kg/m$^2$)</td>
<td>22.7±1.9 (19-25)</td>
<td>22.4±2.6 (17-26)</td>
<td>0.720</td>
</tr>
</tbody>
</table>

of balance exercises using the DIBA differ from those of balance training using standard balance exercises tools such as BOSU, balance boards, wobble board, and a soft cushion block. Following the eight-week balance training and exercise intervention, the DIBA group reached a greater distance on the anterior component of YBT, and had a lower
Table 3. Between and within group comparison of Y-Balance Test scores.

<table>
<thead>
<tr>
<th>Direction</th>
<th>DIBA group Mean±SD (Range)</th>
<th>Control group Mean±SD (Range)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anterior (cm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>77.0±5.8 (66-87)</td>
<td>74.1±5.5 (64-86)</td>
<td>0.134</td>
</tr>
<tr>
<td>4th week</td>
<td>77.3±6.2 (67-90)</td>
<td>75.2±5.4 (66-86)</td>
<td>0.293</td>
</tr>
<tr>
<td>8th week</td>
<td>81.0±6.0 (66-90)</td>
<td>74.7±4.8 (68-86)</td>
<td>0.001**</td>
</tr>
<tr>
<td>p-values</td>
<td>&gt; 0.0167 (Baseline vs. 4th wk)</td>
<td>&gt; 0.0167 (Baseline vs. 4th wk)</td>
<td>&gt; 0.0167 (Baseline vs. 8th wk)</td>
</tr>
<tr>
<td><strong>Posteriomedial (cm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>88.6±9.5 (65-109)</td>
<td>85.9±4.4 (78-93)</td>
<td>0.171</td>
</tr>
<tr>
<td>4th week</td>
<td>88.2±7.6 (68-100)</td>
<td>87.1±5.0 (77-97)</td>
<td>0.406</td>
</tr>
<tr>
<td>8th week</td>
<td>90.8±9.8 (70-115)</td>
<td>87.8±5.3 (80-95)</td>
<td>0.293</td>
</tr>
<tr>
<td>p-values</td>
<td>&gt; 0.0167 (Baseline vs. 4th wk)</td>
<td>&gt; 0.0167 (Baseline vs. 4th wk)</td>
<td>&gt; 0.0167 (Baseline vs. 8th wk)</td>
</tr>
<tr>
<td><strong>Posteriolateral (cm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>91.1±8.3 (74-108)</td>
<td>88.1±4.4 (88-92)</td>
<td>0.226</td>
</tr>
<tr>
<td>4th week</td>
<td>90.1±8.1 (74-107)</td>
<td>90.0±4.5 (81-96)</td>
<td>0.988</td>
</tr>
<tr>
<td>8th week</td>
<td>91.5±7.7 (76-110)</td>
<td>91.6±4.9 (80-98)</td>
<td>0.563</td>
</tr>
<tr>
<td>p-values</td>
<td>&gt; 0.0167 (Baseline vs. 4th wk)</td>
<td>&gt; 0.0167 (Baseline vs. 4th wk)</td>
<td>&gt; 0.0167 (Baseline vs. 8th wk)</td>
</tr>
</tbody>
</table>

* Significant difference at p < 0.05
** Significant difference p<0.0167 (Bonferroni correction)

number of falls on the FBT.

Several authors have suggested that a decrease in lower limb proprioceptive sense after injuries is linked with balance deficits.\(^\text{17-19}\) However, both static and dynamic balance may improve with properly designed exercise and training programs. Muscle spindles and Golgi tendon organs are considered the main proprioceptors,\(^\text{20,21}\) and their function may improve with conditioning and strengthening exercises.\(^\text{21-23}\) There are a number of balance training tools and devices currently used in clinical settings for improving muscle strength and proprioceptive sense in order to increase balance ability following lower extremity injury. Few of them have features of computerized or electromechanically controlled mechanisms and the ability to provide customized training programs.

Most systems lack functionality and the ability to simulate activities of daily life. Ground surface balance training tools are generally fixed to the floor. While most balance training equipment does not provide perturbation, which dynamically challenges participants, the DIBA has dual movable foot platforms allowing for perturbation in mediolateral and anteroposterior directions during different postural conditions such as lunging, squatting, single leg stance with eyes open and closed, and also can be used with additional activities such as throwing and catching ball.

Because physical exercise and training for increasing balance ability requires an individual’s active participation,\(^\text{17,24}\) the DIBA, with its variety of activity combinations was engaging for participants during the eight-week training program. This eight-week duration has also been suggested by Brachmann et al.\(^\text{25}\) for detectable change in balance ability, indeed the results of the current study did not find any significant difference between groups for test scores at the end of the 4th week.

Performing an exercise program on anteroposterior foot platform that could be perturbed during combined activities was more effective in affecting the anterior reach component of YBT than other balance tools. The anterior reach...
of the DIBA group showed a 5.19% improvement while anterior reach of the control group showed only a 0.8% improvement. On the other hand, medial and lateral component scores of the YBT did not demonstrate significant differences between groups (Posteromedial DIBA group 2.48%, control group 0.8%, posterolateral DIBA group 0.43%, control group 3.9%). This may be because the mediolateral perturbation done by the DIBA is not as large as that which occurs in the antero-posterior perturbation. This could suggest that mediolateral perturbation of trunk stability may be increased when the two feet are apart from each other. Consequently, healthy participants without balance deficits may not show improvement in their balance. It would be worthwhile to study this exercise progression for balance training program using the DIBA on people with lower extremity injuries.

Assessment of static balance using FBT showed that number of falls for the DIBA group was less when compared to control group at the end of 8th week. This result may indicate improvement in proprioceptive input that allows for accurate motor responses that function to keep the body’s center of mass over the base of support, which may have been due to the dynamic behavior of the DIBA. Improving proprioceptive acuity of the muscular structures of lower extremity muscles using a dynamic balance training system may improve the afferent contributions of proprioceptors in the muscles such as muscle spindles and Golgi tendon organ, positively affecting balance ability.20 This assertion was not directly studied in this research, however.

Despite the feet being fixed on movable foot platforms when using the DIBA, the distal end of the lower extremity still moves antero-posterior and mediolateral directions, which may be considered an open kinetic chain. However, these movements are not completely unconstrained, as maintaining of balance over the DIBA requires movement of proximal segments. Therefore, the combination of open and closed kinetic chain exercises with the DIBA may be more advantageous than the other balance equipment.

Poor performance on the YBT is associated with an increased risk of variety of lower extremity injuries. Especially, ‘poor performance’ in anterior direction of the YBT (total reach direction and asymmetry), has been shown to have the most consistent relationship with increased injury risk.27,28 Anterior (ANT) reach distance asymmetries greater than 4 cm are associated with a 2.3 to 2.5-time greater risk of lower extremity injury.29 In the current study, healthy subjects in the control group had a mean anterior reach asymmetry of 6.3cm, which is greater than this threshold. This may indicate that the sedentary subjects in the current study were at an increased risk of sustaining a lower extremity injury.

The importance of being able to produce large ranges of hip flexion is supported by the kinetic models for posterior reach distances including hip extensor moments for both posterior medial (PM) and posterior lateral (PL) reaches, and by other studies25,30 which show that hip extension strength is strongly correlated with posterior reach performance. The knee extensor and hip abductor moment explained variance in ANT and PM reaches, while the hip extensor moment explained variance in PL and PM reaches.29,30

This study was limited to the measurement of young healthy individuals; therefore, the results may differ for subjects of different ages and in the presence of clinical conditions. Second, testing of muscle strength that would be worthwhile to investigate to discern whether a change in muscle strength affected measures static and dynamic balance. Thirdly, the study design did not allow any conclusions to be drawn about level of the muscular system at which any adaptations occurred or if these would be transferred to sports movements. Finally, the majority of participants were first year physiotherapy students and therefore may have had some previous exposure to balance training, the effect of which is not known. Tasks were repeated and therefore it is possible that fatigue affected the overall performance. It is possible that a learning effect may have been present. We think that the DIBA would be reliable for doing balance exercises within a healthy population and provide a reference for further clinical studies.

CONCLUSION

The results of the current study indicate that the DIBA may improve balance better than balance exercises using standard balance training tools such as the BOSU, balance boards, wobble board, and a soft cushion block. Clinical improvements in dynamic measures of postural control provide an insight into the use of an alternative form of functional balance training using the DIBA with healthy subjects.

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Cross-sectional Study of EMG and EMG Rise During Fast and Slow Hamstring Exercises

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Background
Hamstring injuries remain a major burden in football while the effective prevention exercise the Nordic Hamstring is poorly adopted, despite the added positive effects on performance. Better understanding of hamstring function during Nordic Hamstring compared to other exercises may provide better insight to the physiological adaptations of different types of hamstring curls.

Purpose
This cross-sectional study therefore aimed to compare the Nordic Hamstring curl with a conventional prone Leg Curl at different loads, and novel high velocity Hamstring Catches; in terms of peak normalized electromyographical activity (nEMG) and rate of electromyographic rise (RER) of Biceps Femoris long head, and angular velocity of the knee.

Study design
Cross-sectional study.

Methods
Out of 28 participants enrolled, the final sample included 23 recreationally active male participants who attended a session for determining RM (repetition maximum) to establish loading (8 and 16RM for Hamstring Catches, and 8, 16 and 24RM for Leg Curl) and to familiarize themselves with the three different exercises (Nordic Hamstring, Leg Curl and Hamstring Catch), and a testing session >4 days after during which EMG data were collected during 3 repetitions of each exercise performed in a random order.

Results
The Nordic Hamstring evoked higher RER (1091.8 nEMG/s) than Hamstring Catches (mean difference: 421 nEMG/s, p<0.0001) and Leg Curl (mean difference: 705 nEMG/s, p<0.001), and at the earliest numerical timepoint from onset of muscle contraction (the Nordic Hamstring: 6 ms; Hamstring Catches: 36-41 ms; Leg Curl: 12-14 ms).
Catches displayed high peak angular velocity (mean: 471°/s). There was no difference in peak nEMG, irrespective of load for Leg Curl (8, 16 or 24RM) or Hamstring Catches (8- or 16RM).

Conclusion
The Nordic Hamstring displayed the highest level muscle activity and most explosive recruitment characteristics with early and high rate of electromyographic rise, compared to even high velocity exercises, thus providing a possible mechanism by which it may increase performance and reduce injuries.

Levels of evidence
3

What is known about the subject
Early phase force and muscle recruitment have been linked to both performance and hamstring-related inhibition and fatiguability. However, the potential for different hamstring exercises to elicit explosive recruitment is unknown.

What this study adds to existing knowledge
Early phase recruitment was higher and faster during the Nordic Hamstring exercise compared with conventional hamstring Leg Curl exercises with different loads and a high-velocity hamstring exercise.

Clinical Relevance
The surprisingly fast and explosive recruitment characteristics during the Nordic Hamstring exercise suggests the possibility that this exercise have the potential to improve the rate of force development and perhaps counter the effects of hamstring-related inhibition and fatigue.

INTRODUCTION
Hamstring injuries remain a continuing burden in football (soccer). A growing body of evidence has established implementation of the Nordic Hamstring (NH) exercise as an effective preventive measure. Although the NH is simple to perform and implement at team level, evidence suggests uptake of NH is poor. Data from clinicians and researchers indicate that this is likely due to concerns about the specificity of NH and other conventional slow strength training exercises for the hamstrings (e.g. Leg Curl) to high-speed running; the most common injury mechanism. High-speed running is characterized by explosive rate of force development (RFD), high knee angular velocity, eccentric peak muscle activity at long muscle lengths of the knee flexors, and multi-joint movement, which may lead to injuries without proper conditioning of the muscle-tendon complex. Conversely, the NH is an isolated knee-flexion exercise performed slowly at short muscle lengths. The ‘Hamstring Catches’ (HC) exercise is performed with rapid eccentric contractions at moderate muscle lengths. A variation of the exercise was recently devised with the goal of achieving higher angular velocity and controlled external loading by using the suspension force of an elastic band; however, no evidence supports its use presently (Supplementary video 1, Hamstring Catches). In contrast, NH and the conventional prone Leg Curl is performed with movement only over the knee joint at primarily short muscle lengths and low velocity. Despite the theoretical concerns with characteristics of NH, data from on-field research has repeatedly shown implementation of the NH exercise decreases new and recurrent hamstring injuries, improvements in sprint and jump performance; as well as eccentric knee flexor strength and muscle architecture of the hamstring muscles associated with decreased risk of hamstring injury. However, it could be that other exercises involving eccentric loads at longer muscle lengths and rapid decelerations would display more specific explosive characteristics, such as high angular velocity, or rate of electromyographic rise (RER) which is closely related to RFD. Such exercises would better fit the concept of exercise specificity and potentially offer a more acceptable alternative or supplement to the NH exercise and conventional slow strength training exercises at different loads in strength and conditioning programmes aimed at reducing injuries and maintaining or improving performance. Previous work on hamstring muscle activity has shown that most conventional hamstring exercises evoke more medial than lateral peak muscle activity, and therefore the distribution of muscle activity between semitendinosus (ST) and the long head of biceps femoris (BFlh) during high velocity exercises and RER extraction is also of interest. In line with this, measuring RER provides the advantage of estimating neural function of specific muscles opposed to joint- or whole-body kinetics, by allowing investigations directly of the most commonly injured long head of biceps femoris (BFlh) rather than the entirety of the knee flexors.

The purpose of this exploratory study was therefore to compare the Nordic Hamstring curl with a conventional prone Leg Curl at different loads, and the novel high-velocity Hamstring Catches; in terms of peak normalized electromyographical activity (nEMG) and rate of electromyographic rise (RER) of Biceps Femoris long head, as well as angular velocity of the knee.
The study used a cross-sectional design in which twenty-eight healthy sports-active males were enrolled through convenience sampling at Hvidovre Hospital, Denmark. A familiarization session was performed at least four days prior to the testing session to familiarize the participants with the experimental procedures and to determine the exercise load. The study was not pre-registered, as it took place before trial-registration was as prevalent as today; however, as this was an exploratory study there were no pre-specified hypotheses or outcomes selected, and the aim was formulated before data collection began. The study was approved by the Danish National Committee on Health Research Ethics (H-3-2011-145) and all participants gave written informed consent according to the Helsinki Declaration. The reporting of the study follows the STROBE guidelines, using the checklist for cross-sectional studies.20

PARTICIPANTS

Participants was eligible for inclusion if aged 18-40 years and also participated systematically in sports more than two and a half hours weekly. Reasons for exclusion included having suffered from any hamstring strain injuries or other serious lower limb injuries in the preceding six months (e.g. ligament tear, fracture, muscle ruptures, major trauma), hamstring pain the week prior to testing or any current delayed onset muscle soreness, or serious pathology or infection near the area of electrode- placement. History of previous hamstring injuries besides during the preceding six months was not captured.

EXERCISES

Slow conventional prone Leg Curl at 8, 16 and 24 RM was performed prone on an examination bed with ankles clear of the bed. An elastic band was fixed around the ankle of the participant at a 45° angle from the floor. The knee was flexed to 90° at a repetition tempo of 3 s concentric phase, 2 s isometric hold, 3 s eccentric phase and a 2 s pause to a pre-recorded instruction.

Slow eccentric training: The Nordic Hamstring (NH) exercise is a partner-assisted exercise where the subject attempts to resist a forward-falling motion using his knee flexors to maximize loading in the eccentric phase, while the partner holds the ankles in place. The participants were asked to keep their hips fixed in a slightly flexed position throughout the whole range of motion, to brake the forward fall for as long as possible using their knee flexors eccentrically, and to try keeping maximum tension in these muscles even after they could no longer control their descent. Subjects were asked to use their arms and hands to buffer the fall, let the chest touch the surface, and then use their arms to get back to the starting position.15

Fast eccentric training: Hamstring Catches with external load of 8 and 16 RM derived from Leg Curl, started with the participants in the same setup and position as during the prone Leg Curl. With the participant instructed to relax the hamstrings, the investigator pulled the restrained foot to 90° knee flexion with one hand while palpating the hamstring muscle belly for noticeable muscle activity with the other. Participants was then instructed to stop or ‘catch’ the lower leg in the range of 45-0° knee flexion once the therapist let go of the ankle at an unknown time within the following 10 s. Once the extension of the knee was halted, participants then relaxed to full extension (Supplementary Video 1)

TEST SESSIONS

Participants attended a familiarization session and an experimental session with a minimum four-day interval to avoid delayed onset of muscle soreness. No exercise was allowed on the day of any of the sessions or the day before. At the familiarization session a 10-min, standardized warm-up of running drills and mobility exercises was performed (light running, while hip-in, hip-out, backwards running, side shuffles, high knees, butt-kicks, skipping, accelerations, and front-back and side-side leg swings), followed by familiarization with the exercises and determination of absolute loads of 8, 16 and 24 repetition maximum (RM) for Leg Curl in a randomized order. This was done with the starting load (comprised of type and length of elastic band) being estimated by the participant in the first set and subsequently adjusted until repetition failure was reached corresponding to the relevant RM-zone (e.g. load resulting in failure on repetition 7 to 9 was used for 8 RM). External load established for 8 and 16 RM Leg Curl was also used for Hamstring Catches. During the experimental session, the participants performed a similar warm-up followed by isometric maximum voluntary contraction (MVC) tests of the knee flexors which were used for normalization of the EMG signal (nEMG). Finally, participants performed three repetitions of each exercise in a random order to avoid the confounding of fatigue. Data from a mean of these three repetitions were used for analyses. Perceived exertion was identified on the Borg CR10 scale21 by participants immediately after exercises and is reported as a descriptive variable.

ELECTROMYOGRAPHY

Rectangular 20 x 30 mm non-disposable differential surface-electrodes (DE-2.1, Delsys, Boston, MA, USA) were unilaterally applied following standard procedures of skin preparation and according to SEINAM placement procedures. Electrodes were placed with electrode gel and medical grade adhesive parallel with presumed muscle fiber direction to collect electromyographic data from BFth and semitendinosus on one leg defined as the preferred kicking leg. Verification of EMG signal quality, that is the presence of artifacts or noise, was conducted by visual inspection of the raw EMG after initial electrode placement and again after the warm-up routine. The electrodes were connected to small built-in preamplifiers and further to a main amplifier unit (Bagnoli-16, Delsys, Boston, USA) with a band-pass of 15–450 Hz and a common-mode rejection ratio of 92 dB. The signals were sampled at 1 kHz using a 16-bit A/D converter (6056E, National Instruments, Austin, TX, USA). Data were obtained and stored on a personal computer (EMGworks acquisition 3.1, Delsys, Boston, USA). A mean was calculated for muscle activity during Hamstring
Catches for up to 0.5 s prior to change in knee flexion angle to post hoc verify the extent of relaxation of the participants hamstrings, which was found to be <6% nEMG for BFh and ST. Two isometric MVCs were performed with participants laying prone on an examination bed with 25° knee flexion and pulled against a fixed belt attached just proximal to the ankle for 5 s with at least 50 s rest between repetitions. All raw EMG signals were filtered using a Butterworth filter (10 Hz cut-off frequency) and subsequently smoothed by a moving root mean square (RMS; 500 ms and 50 ms time constant) filter. Peak nEMG of each muscle within each contraction was identified as the maximum value of the smoothed 500 ms RMS EMG signal and normalized to the maximal 500 ms RMS EMG obtained during MVCs. Fifty ms RMS EMG was used to identify RER, that is, the maximal slope of the rectified smoothed EMG-time curve (ΔnEMG/Δt) defined as exceeding 5% of peak nEMG. Slopes are commonly extracted and presented in the epochs from onset to 30 ms, 50 ms, 100 ms and 200 ms.17

**ANGULAR VELOCITY**

Angular velocity of knee flexion was recorded with a digital goniometer (Delsys, Boston, USA) and extracted using a 50 ms RMS filter. Calibration was done with a manual goniometer for each participant with 90° knee flexion as the reference value during visual inspection.

**STATISTICAL METHODS**

A repeated measures linear mixed model (Proc Mixed, SAS) was used for the evaluation of RER and peak nEMG (dependent variables) for each muscle with exercise as independent variable. Per-protocol analyses was chosen, and no imputation of data points were performed. This decision was made before running any analyses of the data. All nEMG values are reported as least square mean with confidence intervals and level of significance was set at p < 0.05. All data were normally distributed. No statistical inferences were thought needed a priori for evaluating the differences in angular velocity. For evaluation of the ordinal data from perceived exertion, the Wilcoxon Signed-Rank test was performed. If the significance level of p < 0.05 was used. As inferential statistics are performed in spite of an exploratory design, caution is warranted when making inferences. No power-calculation was performed to inform the sample size needed prior to the study.

**RESULTS**

**PARTICIPANTS**

Of 28 participants enrolled in the study, 23 (25.5±4.6 years, 181.5±5.4 cm, 80±9 kg, 7.5±7.3 weekly training hours) were included for final data analyses. Three participants experienced pain during the familiarization session or suffered from a recent acute trauma; data from one participant was incomplete; and another reported back pain during testing session and therefore data from all five participants were excluded from analysis.

**ANGULAR VELOCITY**

The angular velocity of Hamstring Catches 16 RM peaked at 490.1°/s [95%CI: 416-564] and 8 RM at 451.9°/s [95%CI: 429-475] (Table 1). Peak velocity of NH was 100.3°/s [95%CI: 90-111] and the set-tempo Leg Curl exercises peak velocities ranged from 90 to 137°/s.

**PERCEIVED EXERTION OF THE THREE DIFFERENCE EXERCISE TYPES**

Nordic Hamstring (median 5, mean 6.2) and Leg Curl 8 RM (median 5, mean 5.7) reached exertion levels above "hard" (>5), as rated by participants on the Borg CR10 scale. Leg Curl at 16 and 24 RM, and Hamstring Catches at 8 and 16 RM (median range: 3-4, mean range: 5.3-4.1) were perceived as less strenuous with levels between "moderate" and "hard" (3-5). Nordic Hamstring and Leg Curl 8 RM did not differ in levels of perceived exertion (p=0.373), but were perceived to be more strenuous than all other exercises (p=0.037-0.012), which in turn were not statistically different from each other (p=0.571).

**PEAK NEMG**

Peak BFh nEMG did not differ between intensities (8, 16 and 24 RM) during Leg Curl Leg Curl (range: 65-68% nEMG, p=0.6599-0.9386) nor during Hamstring Catches (range: 55-49% nEMG, p=0.6700) (Table 1). Nordic Hamstring and Leg Curl 8 RM and 16 RM generated higher peak BFh activity (range: 65-82% nEMG) than any other exercises (mean difference: 16%, p=0.0429-0.0005), but were not different from each other (p=0.0514-0.1125). With the exception of the Leg Curl 8 RM (ST: 86% nEMG [95%CI: 67-105] versus BFh: 68% nEMG [95%CI: 56-76], p=0.0432) no statistically significant differences in nEMG between ST and BFh were observed (p=0.1047-0.8244), however a numerically higher activity for ST compared to BFh was observed throughout all exercises (Table 1).

**RATE OF EMG RISE**

Peak rate of EMG rise was significantly higher during NH (1091.8 nEMG/s [95%CI: 849-1354]) than during any other exercise (p=0.0002-0.0001) (Figure 1). Hamstring Catches at 8 RM (631.6 nEMG/s [95%CI: 500-763]) and at 16 RM (709.2 nEMG/s [95%CI: 510-908]) were not different from each other (p=0.4169) and both were higher than Leg Curl at 8, 16 and 24 RM (range: 352-406 nEMG/s, p=0.0343-0.0006), between which there were no difference (p=0.9872-0.5870). All exercises reached peak RER within 50 ms after onset of muscle activity (Figure 2), with NH after 5.8 ms [95%CI: 4-8]; Hamstring Catches 8 RM after 36 ms [95%CI: 25-47] and 16 RM after 40.9 ms [95%CI: 24-58]; Leg Curl 8 RM after 23.8 ms [95%CI: 6-41], 16 RM after 12.4 ms [95%CI: 5-19] and 24 RM after 13.7 ms [95%CI: 8-19]. With the exception of the Hamstring Catches 8 RM (ST: 632.2 nEMG/s [95%CI: 497-767] versus BFh: 359.7 nEMG/s [95%CI: 224-495], p=0.0046) no statistically significant differences in RER between ST and BFh were observed (p=0.3693-0.9191), however a numerical higher RER for ST compared to BFh was observed throughout all exercises (12-67% difference).

**Table 1**

<table>
<thead>
<tr>
<th>Exercise Type</th>
<th>Mean nEMG/s (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nordic Hamstring</td>
<td>68% nEMG (56-76)</td>
</tr>
<tr>
<td>Leg Curl 8 RM</td>
<td>86% nEMG (67-105)</td>
</tr>
<tr>
<td>Hamstring Catches 8 RM</td>
<td>631.6 nEMG/s (500-763)</td>
</tr>
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<td>Hamstring Catches 16 RM</td>
<td>709.2 nEMG/s (510-908)</td>
</tr>
</tbody>
</table>

**Figure 1**

Hamstring Catches at 8 RM peaked at 490.1°/s [95%CI: 416-564] and 8 RM at 451.9°/s [95%CI: 429-475] (Table 1). Peak velocity of NH was 100.3°/s [95%CI: 90-111] and the set-tempo Leg Curl exercises peak velocities ranged from 90 to 137°/s.

**Figure 2**

Hamstring Catches at 8 RM (631.6 nEMG/s [95%CI: 500-763]) and at 16 RM (709.2 nEMG/s [95%CI: 510-908]) were not different from each other (p=0.4169) and both were higher than Leg Curl at 8, 16 and 24 RM (range: 352-406 nEMG/s, p=0.0343-0.0006), between which there were no difference (p=0.9872-0.5870). All exercises reached peak RER within 50 ms after onset of muscle activity (Figure 2), with NH after 5.8 ms [95%CI: 4-8]; Hamstring Catches 8 RM after 36 ms [95%CI: 25-47] and 16 RM after 40.9 ms [95%CI: 24-58]; Leg Curl 8 RM after 23.8 ms [95%CI: 6-41], 16 RM after 12.4 ms [95%CI: 5-19] and 24 RM after 13.7 ms [95%CI: 8-19]. With the exception of the Hamstring Catches 8 RM (ST: 632.2 nEMG/s [95%CI: 497-767] versus BFh: 359.7 nEMG/s [95%CI: 224-495], p=0.0046) no statistically significant differences in RER between ST and BFh were observed (p=0.3693-0.9191), however a numerical higher RER for ST compared to BFh was observed throughout all exercises (12-67% difference).
Table 1: Absolute values of variables collected during six hamstring exercises, Mean and 95% confidence intervals

<table>
<thead>
<tr>
<th></th>
<th>Leg curl 8 RM</th>
<th>Leg curl 16 RM</th>
<th>Leg curl 24 RM</th>
<th>Nordic Hamstring</th>
<th>Hamstring Catches 8 RM</th>
<th>Hamstring Catches 16 RM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knee angle at peak nEMG of BFh</strong> † (°)</td>
<td>76.2 [71-81]</td>
<td>74.9 [71-79]</td>
<td>75.1 [69-81]</td>
<td>59.6 [51-68]</td>
<td>47.1 [43-51]</td>
<td>44.3 [40-49]</td>
</tr>
<tr>
<td><strong>Peak muscle activity of BFh (% nEMG)</strong></td>
<td>68 [60-76] † ‡</td>
<td>64.8 [57-73] † ‡ §</td>
<td>64 [56-72] † ‡ §</td>
<td>82 [71-93] †</td>
<td>53.2 [43-63] ‡ §</td>
<td>49.4 [40-59] §</td>
</tr>
<tr>
<td><strong>Peak muscle activity of ST (% nEMG)</strong></td>
<td>85.9 [67-105] †</td>
<td>79.1 [62-97] †</td>
<td>76.7 [60-94] †</td>
<td>91.7 [80-104] †</td>
<td>56.7 [49-65] ‡</td>
<td>51.4 [45-58] ‡</td>
</tr>
</tbody>
</table>

* = variables not tested for significance; † = variables not different from each other (p<0.05); ‡ = variables not different from each other (p<0.05); § = variables not different from each other (p<0.05); RM = repetition maximum; nEMG = normalized electromyography; RER = rate of EMG rise; BFh = Biceps Femoris long head; ST = Semitendinosus

**DISCUSSION**

The purpose of this study was to quantify the extent of peak and explosive muscle activity to characterize and compare the slow eccentric NH exercise, slow conventional prone Leg Curl, and fast eccentric Hamstring Catches with each other. The Nordic Hamstring exercise evoked the highest peak muscle activity whereas Hamstring Catches evoked the lowest. Besides RER data on Hamstring Catches 8RM, all exercises in the present study displayed numerically higher nEMG (6-26% nEMG difference) and RER (12-76% nEMG/s difference) in ST than BFh, in line with previous data showing ST being more active during most hamstring exercises. Surprisingly, the NH exercise showed the highest rate of EMG rise at a very early time point in muscle contraction, even compared to the high velocity Hamstring Catches.

The levels and relationships of peak muscle activity between muscles and exercises found in this study, are consistent with other findings during hamstring exercises. Only NH and Leg Curl exercises, which were also the exercises perceived to be most strenuous, evoked BFh nEMG of >60%, a minimum intensity level recommended to promote longitudinal strength gains. The most surprising finding was the peak rate of EMG rise during NH after just 6 ms at a rate of 1092 nEMG/s compared to the high velocity Hamstring Catches (8 RM: 652 nEMG/s at 36 ms; 16 RM: 709 nEMG/s at 41 ms), indicating a fast and explosive pattern of muscle activity. This could be due to the very sudden onset of force exertion during the NH, in which the hamstrings need to instantly control and decelerate a long and heavy lever (from knee joint and up with high proportion of the total body mass). In contrast, during Hamstring Catches, the hamstrings were allowed delayed force exertion until reaching the 45-0° knee flexion range of motion, perhaps thereby slowing the rate of muscle activation. Nevertheless, this seems to characterize NH as a heavy low velocity eccentric exercise with explosive recruitment characteristics. The rate of EMG rise values attained during the slow conventional prone Leg Curl (range: 350-406 nEMG/s) is comparable with previous data obtained from soccer players during isokinetic testing. The slightly higher values from the current data could be due to the more unstable nature and
slightly inconsistent rate of loading of the elastic bands utilized compared to isokinetic testing, possibly requiring faster muscle activation to confidently adhere to the tempo and withstand the backwards force of the band. As for the nEMG levels, peak RER, and time of peak RER obtained for ST were similar to BFlh in the present study.

The highest documented and quantified angular velocity using a controlled external load during concentric hamstring exercises is 450°/s isokinetically\(^\text{25}\) which is comparable to our recordings during Hamstring Catches (8 RM: 452°/s; 16 RM: 490°/s). Although >180°/s is usually defined as high velocity exercise in the literature, the angular velocity of knee extension during sprinting has been documented at more than 1000°/s,\(^\text{10}\) making Hamstring Catches a high velocity exercise, but still lacking some velocity in terms of specificity to high-speed running. The explosive recruitment characteristics combined with the eccentric contraction mode during NH could partly explain the positive longitudinal effects of NH on sprinting and jumping ability.\(^\text{14}–\text{16}\) Eccentric hamstring training is known to be essential for sprint and change of direction abilities,\(^\text{8,24,25}\) and produce increased eccentric and concentric RFD which is predominantly determined by early phase neural adaptations.\(^\text{17,25}\) In line with this, eccentric training has been reported to preferentially activate high threshold motor units\(^\text{26}\) and lower neural inhibition.\(^\text{17,25,27}\) Training with ballistic or high velocity muscle actions can also increase RFD and lead to velocity specific strength gains, by improving neural drive in early phase muscle contraction.\(^\text{5,25,28–30}\) In accordance with this, unpublished data from our group have shown a six week intervention of NH was superior to the ballistic exercise Kettlebell Swing in improving early-phase isometric hamstring RFD (Ishoi et. al. unpublished), while other data from elite footballers show associations between early phase RFD and sprint performance.\(^\text{31}\) Combined, the observations of explosive and eccentric nature of muscle activity during NH seen in the early phase of muscle contraction, might explain some of the effects seen in high-velocity characteristics skills, such as RFD ability, high velocity strength gains,\(^\text{32}\) and sprint and jumping performance; despite it being performed at slow angular velocity. In terms of injury reduction perspectives of the current data, the early and high eccentric RER during NH could be characteristics that target BFlh-specific neural inhibition seen in either previously injured athletes\(^\text{33}\) or acutely at-risk athletes displaying inhibition in a state of fatigue.\(^\text{22,34}\)

The NH exercise has previously been reported to increase eccentric hamstring strength at higher velocities than those at which the exercise is performed\(^\text{22}\) while other data show adaptations following eccentric training is velocity specific.\(^\text{28,29}\) Even though NH seems to provide numerous positive physiological and performance adaptations in spite of the low velocity contractions at short to moderate muscle lengths, data suggest contractions at long muscle lengths and high velocity can also make positive changes to morphology and performance\(^\text{5,19,25,28,29}\) which would better fit the concept of exercise specificity.\(^\text{5,19}\) Therefore, eccentric Hamstring Catches performed at high velocity and longer muscle lengths, showing greater RER than conventional resistance training exercises, could be a useful supplement in either rehabilitation or injury prevention programs.

**Figure 1: Peak rate of EMG rise in Biceps Femoris**

BFlh = Biceps Femoris long head; nEMG/s = percentage of normalized electromyography change per second. * = variables not different from each other (p>0.05); † = variables not different from each other (p<0.05). Error bars represent the upper limits of 95% confidence intervals.

**Figure 2: Mean rates of EMG rise in intervals of early phase contraction in Biceps Femoris**

BFlh = Biceps Femoris long head; nEMG/s = percentage of normalized electromyography change per second. Error bars represent the upper limits of 95% confidence intervals.

**METHODOLOGICAL LIMITATIONS**

Any potential future studies including Hamstring Catches should aim to include previously injured players, either at some stage in rehabilitation or after they return to play, and preferably in a prospective study design. The same limitations and pitfalls inherent to measuring surface EMG would also apply to the RER measures. The peak velocity during the slow fixed tempo prone Leg Curl were in the range 91-156°/s, in contrast to what was observed during experimental sessions when athletes followed a voice-recording dictating a tempo of three seconds eccentric and concentric phases which would correspond to 30°/s. This could be attributed to the small perturbations from athletes constantly trying to stabilize the elastic band which the high sampling frequency would have detected as valid data points.
PRACTICAL APPLICATIONS

The surprisingly fast and explosive recruitment characteristics during the NH exercise suggests the possibility that this exercise have the potential to improve the rate of force development and perhaps counter the effects of hamstring-related inhibition and fatigue.

Data from Hamstring Catches highlight a potential for the exercise when there is a need for eccentric exercises more specific to high-speed running in regards to high angular velocity (range: 452-490°/s vs. >1000°/s during sprinting) and eccentric contractions at longer muscle lengths with increased acceleration of muscle activity at moderate intensity levels. The exercise could potentially be implemented before commencing high-speed running drills and decelerations in rehabilitation. Another benefit of Hamstring Catches is that they can be performed with an elastic band on an examination table or training bench, opposed to requiring heavy, immobile, or costly equipment. To further adjust the muscle lengths, angular velocity or load when applying the exercise in the clinic, a wedge could be inserted under the hip, the suspension force of the band could be increased, or the athlete could be asked to catch their lower leg at different target angles.

CONCLUSION

The NH displayed not only the highest muscle activity, but also most explosive recruitment characteristics with early and high electromyographic activity rise compared to even high velocity exercises. This could be a contributory mechanism by which the NH reduces inhibition, and thereby increases performance and reduces injuries. The devised Hamstring Catches were performed at high velocity and displayed more explosive muscle activity than conventional prone Leg Curl and may provide a useful exercise-based supplement in late phase rehabilitation with higher transfer of training potential in relation to high-speed running.

CONFLICTS OF INTEREST AND SOURCE OF FUNDING

The study received no specific funding. Anthony J. Shield is a co-inventor of a device employed to assess eccentric knee flexor strength (PCT/AU2012/001041.2012) and is also a shareholder in a company responsible for commercialising the device; he was not involved in data collection or analysis in the present study. Besides this, the authors declare no conflict of interest.

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REFERENCES


SUPPLEMENTARY MATERIALS

Video 1
Download: https://ijspt.scholasticahq.com/article/25364-cross-sectional-study-of-emg-and-emg-rise-during-fast-and-slow-hamstring-exercises/attachment/64507.mp4?auth_token=msF1cPCn4Z2cr42jrUCg
The Role of Fatigue in Return to Sport Testing Following Anterior Cruciate Ligament Reconstruction
Justin C Tallard, PT, DPT, SCS, CSCS1, Corbin Hedt, PT, DPT, SCS, CSCS1 2, Bradley S Lambert, PhD1, Patrick C McCulloch, MD1
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Keywords: acl, hop testing, knee, lower extremity, return to sport testing, movement system
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Background
Fatigue may play a role in anterior cruciate ligament (ACL) injury, but has not been incorporated into objective test batteries for return to sport decisions following ACL reconstruction (ACLR) surgery. The effect of fatigue on muscle function and performance following surgery and rehabilitation has been poorly studied.

Purpose/Hypothesis
The purpose of this study was to assess the effect of fatigue on performance of various hop tests used in clinical rehabilitation settings by examining LSI scores. The authors hypothesized that participants will have worse limb symmetry index scores following the fatigue protocol and that the operative limb (ACLR) will have a greater decline in function than the non-operative limb (CON).

Study Design
Cross-Sectional Study.

Methods
Participants (n=21 [Male = 15, Female = 6]; AGE = 24.6 ± 9.3) were at least six months post ACLR and in rehabilitation. Testing was performed over two separate sessions in either a non-fatigued (NFS) or fatigued state (FS). In the FS, individuals performed a series of exercises to exhaust muscular endurance, strength, and power systems, after which they performed as battery of seven hop tests (single hop for distance, triple hop for distance, crossover hop for distance, 6-meter timed hop, lateral rotation hop for distance, medial rotation hop for distance, and vertical jump for height). A 2(limb) x 2(time) ANOVA was used to compare limbs between each state.

Results
Differences between limbs (CON vs ACLR) were observed for all hop tests in the NFS whereby the ACLR limb was observed to have reduced performance (↓ 5.4-9.1%, p<0.05). When tested in the FS, significant differences in performance between limbs remained for only the crossover (↓ 4.9%), medial rotation (↓ 7.1%), lateral rotation (↓ 5.5%), and vertical hop (↓ 10.0%) (p<0.05). When comparing the NFS and FS states, only the CON limb was observed to have significant decreases in performance of the Triple Hop (↓ 7.4%), Crossover (↓ 8.7%), and Lateral Rotation (↓ 5.2%) (p<0.05).

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CONCLUSIONS

Following ACL reconstruction, there appears to be a greater loss in jump performance in the CON limb in the FS. These findings suggest it may be crucial to consider and assess the endurance of both limbs rather than just the ACLR limb when determining readiness for return to play.

LEVEL OF EVIDENCE

Level 3

INTRODUCTION

Anterior cruciate ligament (ACL) injuries can be devastating for athletes across many sports and age groups. In the United States, there are between 100,000 and 200,000 ACL injuries per year.1 Athletes who experience an ACL injury typically miss extended periods of sports participation and suffer both short and long-term consequences including functional limitations, muscle weakness, and most significantly chronic knee pain and osteoarthritis.2 Almost 50% of active individuals who undergo ACL reconstruction suffer a second ACL injury in the first two years after surgery.1,2 This increased risk exists not only for the ipsilateral limb, but the contralateral limb as well. Multiple studies have shown that contralateral injuries occur more often than ipsilateral injuries, especially in female athletes.3–5 Not only do individuals suffer subsequent ACL injuries, but individuals are at increased risk of secondary meniscus injury following ACL reconstructions. Up to 50% of individuals undergo meniscus surgery following return to play after ACL reconstruction.1,2 Predictors of primary and secondary ACL injuries include younger age and participation in sports that involve jumping, pivoting and cutting.1,2 A proposed additional risk factor includes exercise-induced decreases in a muscle’s ability to produce force or power, also known as neuromuscular fatigue.6 Neuromuscular fatigue has frequently been accepted as a risk factor, but its full role in ACL injury is not yet known. It is suggested that fatigue results in reduced muscle strength, and potential alteration in lower extremity kinematics.6,7 It is worth noting that the definition of, and factors that affect neuromuscular fatigue are numerous and defining these is outside of the scope of this study.

The primary reason for undergoing ACL reconstruction is the intent to return to sports.1,2 Health care professionals, responsible for the rehabilitation of individuals following surgery, attempt to mitigate the risk of secondary injury through the use of objective return to sport criteria. These criteria typically include the establishment of a Limb Symmetry Index (LSI) in tests such as quadriceps muscle strength, single leg hop tests, agility, etc. LSI compares the affected limb to the uninvolved limb, using the uninvolved limb as a reference standard and “healthy” control.8 Despite the use of strict return to sport criteria including LSI, under 14% of individuals meet these standards (isokinetic strength testing, hop testing, etc.) within six months.9 Current practice patterns suggest that rehabilitation professionals do not implement objective testing as frequently needed, and when these tests are implemented the standards for safe return to play (RTP) are not met.9–12

Despite numerous research studies and publications, there remains no gold standard for objective RTP criteria, and secondary injury rates remain high. It remains to be seen if LSI provide clinicians any meaningful data beyond that of symmetry. The use of the unaffected limb as a “control” may not be appropriate given that there are bilateral muscle strength, endurance, power, and rate of force development deficits following ACL injury.8 Though studies exist to assess overall resistance to fatigue (YoYo Fitness Test, Lower Extremity Functional Test), the overall effect on movement and injury risk following ACL injury remains to be seen.12 Furthermore, current assessment methods for RTP fail to account for the effects of fatigue on performance, the individuals’ overall endurance and fitness level, or its effects on movement quality.13–15 ACL rehabilitation can last anywhere from six to 12 months resulting in a significant period of changed activity levels. Investigations have shown that long periods of relative inactivity and reduced training volume result in significant reductions in functional capacity. These deficits are sustained locally in the affected limb, as well as globally throughout the rest of the body.8,9

While previous authors have attempted to determine the effect of fatigue on ACL injury risk, or to qualitatively assess fatigue’s effect on kinematics and kinetics, there has yet to be a study assessing fatigue’s effect on performance on objective RTP criteria.3,4,11 As a result, the purpose of this study was to assess the effect of fatigue on performance of various hop tests used in clinical rehabilitation settings by examining LSI scores.2,8,9 It was hypothesized that individual hop distances would be lower for the operative limb (ACLR) than the non-operative limb (CON) in a fatigued state (FS), and that overall LSI scores would be lower in the fatigued versus non-fatigued states (NFS).

MATERIALS AND METHODS

PARTICIPANTS

Approval was first obtained by the Houston Methodist Institutional Review Board (IRB) and written informed consent and/or parental permission were obtained prior to testing from all participants and/or the parent/guardian. This study included individuals undergoing rehabilitation following ACLR (n=21). Participants were recruited from physical therapy clinics within the local hospital network between 2018 and 2020. All participants were at or after six months post-operative, and had been deemed ready for RTP testing by their treating rehabilitation specialist or physician. Each participant passed objective testing with >90% limb symmetry in the clinic or rehabilitation setting with their respective rehabilitation specialist (including Y-balance testing, single leg step down test, 1 repetition max.
testing for leg press and hamstring curl, and isometric strength testing via hand-held dynamometer). Specific inclusion criteria included (1) unilateral ACLR, (2) completion of formal rehabilitation program following surgery (including, but not limited to: strength and conditioning training, power and plyometric training, and agility training) (3) deemed appropriate for RTP testing by treating rehabilitation specialist, and (4) planned to return to cutting and pivoting sports. The rehabilitation program after ACLR was not monitored or controlled by this study. Participants were included in this study regardless of graft type (patellar bone-tendon-bone autograft, hamstring tendon autograft, and allograft). Additionally, those with meniscus repair or partial meniscectomy at time of ACL reconstruction were included. Exclusion criteria included (1) age <16 or >50, (2) further injury or surgery that would preclude standardized rehabilitation protocols for ACL rehabilitation.

OBJECTIVE CRITERIA MEASURES

Objective criterion for RTP used in this study were based on recommendations in the literature. This included quadriceps and hamstring strength measurements, and single leg hop tests (single hop, triple hop, crossover hop, 6-meter timed hop, vertical jump, medial rotation hop, lateral rotation hop, and vertical jump).1–5,6–9,15 The selected measures were determined based on common tests seen in the literature to assess single and multi-planar movement ability, power production, and neuromuscular control. (Figure 1). Prior to all testing, participants completed a 15-minute dynamic warm-up including high knees, butt kicks, leg swings, lateral shuffles, carioca shuffles, A-skip, and other activities designed to prepare individuals for movement as directed by their treating therapist.

Participants completed two separate hop testing sessions after they met inclusion criteria. Testing consisted of a NFS test session (control test), and a FS test session; each performed on a separate day within one week of the first test session to prevent any variance in results due to neuromuscular or strength adaptations. Participants were randomized to perform testing in a NFS or a FS first based on enrollment in the study; with odd numbered participants performing NFS testing first, and even numbered participants performing FS testing first.

FATIGUE PROTOCOL

To achieve fatigue in participants prior to FS testing, a fatigue protocol was developed based on existing literature (Figure 2).16–20 Prior to performing single leg hop tests, participants performed the fatigue protocol until achieving fatigue. Fatigue was defined as an inability to reach 70% of maximal counter-movement jump (CMJ) height two times consecutively.15,17,18 First, maximal CMJ was measured with a vertical jump height device (Vertec, PeformBetter, Rhode Island, US) by taking the highest of three trials for maximum jump performance.19 Researchers calculated and marked 70% of the participants maximal CMJ on the Vertec. Participants then performed one practice trial of the activities within the fatigue protocol that consisted of four exercises performed consecutively upon completion. Exercises were performed in the following order: 10 bodyweight squats to at least 90 degrees of knee flexion, five single leg non-counter movement jumps from a standard 18 inch box, two maximal CMJs, and a 20 yard sprint. Close observation was provided throughout the fatigue protocol to ensure quality movement and appropriate effort throughout. After completing the protocol, participants re-tested maximal CMJ with the Vertec two times consecutively; if participant’s new CMJ height was greater than the 70% fatigue threshold, they were directed to perform the fatigue protocol again. Once the subjects’ CMJ fell below 70% on two consecutive attempts, the fatigue protocol was terminated.

Upon achieving fatigue as defined by this study, participants were asked to give a rating of perceived exertion.
(RPE) for their overall perception of fatigue. Participants were shown a standard Borg RPE scale, from 6 to 20; 6 meaning "no exertion at all" and 20 meaning "maximal exertion". RPE is commonly used to determine activity and session intensity and was developed to estimate individual's heart rate based on how they feel. Single leg hop testing was then initiated within 30 seconds of completion of the fatigue protocol to ensure fatigue was present during testing.

**SINGLE LEG HOP TESTS**

Participants performed the seven single leg hop tests in the following order: single hop for distance, triple hop for distance, crossover hop for distance, 6-meter timed hop, lateral rotation hop for distance, medial rotation hop for distance, and vertical jump for height. Four of these hop tests are commonly used clinically and have good measurement reliability in individuals following ACL reconstruction. Participants completed a practice trial for each hop prior to performing three measured trials for the ACLR and CON limb, with limbs being tested in random order. Participants were given sufficient attempts, within reason, to successfully achieve three hops where they "stuck the landing"; meaning they were able to maintain single limb balance for >2 seconds after landing. If participants were unable to achieve three successful hops, data was recorded for the number of available hops. Quality of these jumps was not assessed as without motion capture technology this is a purely subjective measure, and is beyond the scope of the current study. The average of the three trials was utilized to calculate a LSI for hop testing: for distance and height measures $\text{LSI} = (\text{ACLR average}/\text{CON average}) \times 100\%$; for 6-meter timed hop $\text{LSI} = (\text{ACLR average}/\text{CON average}) \times 100\%$. A total LSI for all seven single leg hop tests was created as the mean of each individual score. A LSI less than 100% represents a deficit in the involved limb.

**STATISTICAL ANALYSIS**

All data were analyzed using SPSS (version 23.0 for Windows, SPSS Inc., Chicago, Illinois). A 2 (fatigue state) by 2 (limb) mixed model ANOVA was used to determine and compare the effects of fatigue within and between each limb (operative & non-operative). Significant interactions indicated by Type III tests of fixed effects were then followed by a Tukey’s post-hoc test for pairwise comparisons. In addition, a paired samples t-test was used to compare the ratio of ACLR to CON limb measures in the NFS and FS. The threshold for statistical significance was set at $p<0.05$. For all significant pairwise comparisons, effect size was calculated using a Cohen’s $d$ statistic whereby effect size (ES) was interpreted as follows: <0.1, Negligible (N); 0.1-0.5, Small (S); 0.5-0.7, Moderate (M); 0.5-0.7, Large (L); >0.7, Very Large (VL).

**RESULTS**

There were a total of 21 subjects in this study (15 male, 6 female) and their demographic and testing information can be found in Table 1.

**HOP TESTING RESULTS**

**Single Leg (Figure 3A):** The ACLR limb was observed to have reduced hop distance compared to the CONTROL limb in the NFS ($p=0.002$, Mean Individual Diff. = -15±3cm, ES=0.40(M)) that was not observed in the FS. This resulted in a significant change in CON / ACLR limb symmetry between the NFS and the FS ($p=0.010$, ES=0.42).

**Triple Hop (Figure 3B):** The ACLR limb was observed to have reduced hop distance compared to the CON limb in the NFS ($p=0.005$, Mean Individual Diff. = -27±8cm, ES=0.24(S)) that was not observed in the FS. Only the CON limb was observed to have a decrease in hop distance between the NFS and FS ($p=0.045$, Mean Individual Diff. = -37±17cm, ES=0.28(S)).

**Crossover (Figure 3C):** The ACLR limb was observed to have reduced hop distance compared to the CON limb in the NFS ($p=0.008$, Mean Individual Diff. = -28±9cm, ES=0.23(S)) and FS ($p=0.005$, Mean Individual Diff. = -21±7cm, ES=14(S)). Only the CON limb was observed to have a decrease in hop distance between the NFS and FS ($p=0.016$, Mean Individual Diff. = -41±16cm, ES=0.34(M)).

**6 Meter (Figure 3D):** The ACLR limb was observed to have an increased 6 Meter hop time (reduced performance) com-
Table 1. Descriptive Statistics for Participant Demographics, Fatigue Protocol Completion Time, and Rating of Perceived Exertion.

<table>
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<th>Age</th>
<th>Sex</th>
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<th>Time to Fatigue</th>
<th>RPE</th>
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Mean/Total: 24.57 M = 15; F = 6

Abbreviations: M, male; F, female; RPE, rating of perceived exertion. Time to fatigue listed as hours:minutes:seconds. RPE utilizing Borg Scale (6 to 20).

pared to the CON limb in the NFS [p=0.014, Mean Individual Diff.= -0.12±0.04 seconds, ES=0.56(M)] that was not observed in the FS.

Medial Rotation (Figure 3E): The ACLR limb was observed to have reduced medial rotation compared to the CON limb in the NFS [p=0.0002, Mean Individual Diff.= -14±3cm, ES=0.35(M)] and FS [p=0.005, Mean Individual Diff.= -12±5cm, ES=0.28(S)].

Lateral Rotation (Figure 3F): The ACLR limb was observed to have reduced lateral rotation compared to the CON limb in the NFS [p=0.002, Mean Individual Diff.= -10±3cm, ES=0.26(S)] and FS [p=0.032, Mean Individual Diff.= -8±4cm, ES=0.21(S)]. Only the CON limb was observed to have a decrease in hop distance between the NFS and FS [p=0.009, Mean Individual Diff.= -8±5cm, ES=0.21(S)].

Vertical (Figure 3G): The ACLR limb was observed to have reduced vertical hop height compared to the CON limb in the NFS [p=0.002, Mean Individual Diff.= -4±1cm, ES=0.36(M)] and FS [p=0.004, Mean Individual Diff.= -3±1cm, ES=0.39(M)].

DISCUSSION

The purpose of this study was to assess the effect of fatigue on LSI during the performance of hop tests in non-fatigued versus fatigued states, post-ACLR with the intention of informing RTP decision making. Results from this study showed that in a NFS, the CON limb generally exhibited improved performance versus the FS on several hop tests. Additionally, in the NFS, participants were able to jump further, higher, and faster on their CON limb as compared to their ACLR limb. Conversely, in a FS, an ACLR to CON com-

Figure 3C. Descriptive Statistics for CONTROL and ACLR Hop Testing Results in a Fatigued and Non-Fatigued State.

Abbreviations: CONTROL, non-operative limb; ACLR, operative limb. P-values: *, significant difference from pre to post fatigue within the same limb (p<0.05); **, significant difference from pre to post fatigue within the same limb (p<0.01); #, significantly different from non-op limb at same time point (p<0.05); ##, significantly different from non-op limb at same time point (p<0.01); ^^, significantly different from non-op limb for %change (p<0.05). Values are Mean ± SD.
parison indicates that jump distance, heights, and times were closer in magnitude. These results did not support the researcher’s original hypothesis that a fatigued state would have a greater effect on the ACLR limb. However, the most relevant finding of this study was that fatigue had a greater effect on the non-operative (CON) limb. Although the magnitude of differences within and between limbs across differing states of fatigue was generally small to moderate (ES=0.14 – 0.40), these data may provide useful information for future studies that examine fatigue and return to sport protocols, and highlight the potential role of fatigue as it pertains to injury risk for the non-operative limb in the early phases of return to sport participation.

A litany of research has been performed on the rehabilitation aspect of ACL reconstruction to date. However, there has been relatively little consensus throughout the literature on which measures are most clinically appropriate and whether or not fatigue should be considered during examination. Based on results of the current study, clinicians can be better informed on the clinical relevance of LSI and how fatigue may affect reported scoring measures.

Possible factors contributing to the current results include: (1) an overall detraining effect as a result of injury, surgery, and inactivity, and (2) a greater effect of said detraining on the unaffected limb as a result of increased focus by rehab clinicians on the operative limb. Previous authors have suggested that detraining occurs bilaterally as a result of injury and lengthy periods of altered activity levels.8,9,26–31 Future studies should attempt to screen for endurance prior to testing, but it remains possible that the current results indicate a neglect of the unaffected limb during rehabilitation, or a reduced resistance to fatigue.

Tests of limb symmetry are the most commonly used and reported objective criteria for determining readiness for RTP.6,8,9,26,27,29 Scores of <90% are indicative of a higher risk for re-injury, and current clinical commentary defines >95% as a more meaningful score for a successful and efficacious return to sport.8,29,30 These studies propose caution when interpreting limb symmetry scores, however, as function could actually be over-estimated with objective testing batteries – even when achieving “passing criteria” an athlete’s readiness to return may not be comprehensively reported.8,18 Fatigue is an under-reported element of return to sport assessment, and may provide valuable information in refining limb symmetry batteries.

The present study is not without limitations. First, fatigue is difficult to quantify and measure; there are multiple factors that affect the presence of fatigue, multiple forms of fatigue (cognitive, neuromuscular, etc.), and varying objective definitions of what is “a fatigued state”. Without the presence of live monitoring data such as a heart rate monitor or other biometric measurements, actual state of “fatigue” is unknown and could have been affected by the small time gap between the collection of RPE, and initiation of testing. The investigators attempted to account for this with a less than 30 second turnover to begin testing. Due to a lack of literature defining fatigue in an ACL population, the current study was designed to induce fatigue across multiple energy systems. Further investigation into objective measures of fatigue would benefit future research. Second, although the most common RTP testing criteria were used, there were other aspects of RTP testing that could be affected by fatigue including qualitative movement analysis and psychological/psychosocial variables of performance that were not accounted for. Future studies should aim to assess both quantitative and qualitative movement analyses in order to create a more complete picture of the effect.
fatigue has on movement following ACL reconstruction. Third, post-operative rehabilitation leading up to the study was not controlled, and may have varied greatly based on the treating rehabilitation specialist; this is an important factor to consider as treatment varies significantly based on clinical specialty and experience level. Based on the results of the current study, it is possible that increased focus on the CON throughout the course of rehabilitation could have altered results. Mirkov et al. and Hiemstra et al. highlight the effect of initial ACL injury on both the contractile and neural properties of the muscle, but as a whole, current studies fail to fully quantify and explain the magnitude of the detraining and initial injury on the CONTROL limb. As a result, further investigation into the effects of ACL injury on the unaffected limb is warranted.

CONCLUSION

The results of this study provide insight into the effect of fatigue on hop performance in individuals following ACLR which may inform RTP considerations. The results indicate that the effect of fatigue on the ACLR was generally less than on the CON limb for the given measures, which could have profound implications for RTP decision making when utilizing LSI as a criterion for RTP. As a result, the sole use of LSI in determining readiness for RTP may not be sufficient. Further research into the effect fatigue has on objective measures is needed to improve clinician’s decision making regarding RTP following ACL reconstruction. Although the full extent of the role of fatigue in ACL rehabilitation is not yet known, the findings in this study indicate that assessment of both limbs should be considered rather than just the ACLR limb when determining RTP criteria.

CONFLICT OF INTEREST

All authors declare no conflicts of interests.

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Figure 3G. Descriptive Statistics for CONTROL and ACLR Hop Testing Results in a Fatigued and Non-Fatigued State.

Abbreviations: CONTROL, non-operative limb; ACLR, operative limb. P-values: *, significant difference from pre to post fatigue within the same limb (p<0.05); **, significant difference from pre to post fatigue within the same limb (p<0.01); #, significantly different from non-op limb at same time point (p<0.05); ##, significantly different from non-op limb at the same time point (p<0.01); ^^, significantly different from non-op limb for % change (p<0.05). Values are Mean ± SD.
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The Non-injured Leg Can Be Used as a Reference for the Injured Leg in Single-legged Hop Tests

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Keywords: hop tests, lower extremity injuries, return to sport

Background

Single-legged hop tests are frequently used in substantiating return to sport decisions following lower extremity injury. Evidence for using the non-injured leg as a reference for the injured leg in the return to sport decision-making at the criterion-based point of return to sport following lower extremity injury is lacking.

Purpose

To compare absolute values in single-legged hop tests between the non-injured leg of athletes returning to high-impact sports after lower extremity injury and the matched leg of healthy athletes.

Study Design

Cross-sectional study.

Methods

One hundred and sixty-nine athletes returning to high-impact sports after lower extremity injury and 169 matched healthy athletes executed five single-legged hop tests. Differences between athletes returning to high-impact sports after lower extremity injury and matched healthy athletes on five single-legged hop tests were analyzed using paired t-tests.

Results

There were no statistically significant differences between the non-injured leg of athletes returning to sport and the matched leg of healthy athletes. Effect sizes ranged from 0.05 to 0.14 indicating negligible effects.

Conclusion

Clinicians can use the non-injured leg as a reference for the injured leg in single-legged hop tests for deciding on return to high-impact sports after lower extremity injuries.

Level of Evidence

3b
INTRODUCTION

Lower extremity injuries frequently occur in the athletic population with more than half occurring during high-impact sports.1 For most injured athletes it is important to return to their pre-injury sports level,2 but only 52%-65% actually achieve this.3-5 In addition, athletes returning to sport have up to 25% (re-)injury risk, often at an early stage of the return to sport (RTS) period.6-9 Low rates of returning to pre-injury sports level and high risks of second injury after RTS highlights the importance of accurate RTS decision-making.10,11

In multidimensional RTS decision-making,12,13 hop tests play an important role in measuring functional performance.14,15 Single-legged hop tests assess the performance of the entire lower extremity and athletes’ ability to perform components of sport-specific actions such as hopping.16 It has been suggested that an athlete is ready for RTS when the Limb Symmetry Index (LSI) is ≥90%, implying that performance of the injured leg corresponds to 90% or more with the non-injured leg.15,17-21 However, the LSI is a controversial construct as deficits of the injured leg could be underestimated when using the detrained non-injured leg as a reference standard.11,22–26 In comparison with healthy athletes, strength and performance deficits of both the injured and non-injured leg have been found following anterior cruciate ligament reconstruction (ACLR).11,22–25,27 When clinicians rely on using the possibly detrained non-injured leg as a reference for the injured leg in RTS decision-making following ACLR, athletes could more easily attain an LSI of ≥90%,11,22–25 This may result in premature RTS clearance possibly leading to a higher risk for a (re)injury.28-31

Although the hop tests and the LSI were designed to support RTS decision-making after anterior cruciate ligament injury (ACLI) or ACLR,16,52 these hop tests are also used in clinical practice to make RTS decisions after other lower extremity injuries of the hip,33 ankle,35,34 and the hamstring(s).35 While the studies regarding bilateral deficits after ACLR included athletes at a time-based approach when athletes might not even be ready for RTS,11,14,22–25,27,36 no studies have investigated differences in hop tests in athletes who were, according to their physical therapists, at the criterion-based point of RTS and ready for RTS following different types of lower extremity injuries compared with matched healthy athletes. This may provide clinicians information regarding whether or not the non-injured leg can be used as a reference standard for the injured leg that is essential to substantiate the criterion based RTS decision-making following lower extremity injuries. Therefore, the primary purpose of this study was to compare performance in single-legged hop tests between the non-injured leg of athletes returning to high-impact sports after lower extremity injury (RTS athletes) and the matched leg of healthy athletes. In addition, this study aimed to assess differences in LSI and absolute values for the injured and matched leg between RTS athletes and healthy athletes.

MATERIALS AND METHODS

A cross-sectional study was conducted in primary care physical therapy practices in the Netherlands between April 2018 and November 2018. The study was approved by METC Zuyderland Zuyd Heerlen, the Netherlands (METCZ20180024). Written informed consent was obtained from all athletes.

PARTICIPANTS

Twenty-eight physical therapists, studying for a sports physical therapy master’s degree in the same educational institution, recruited and tested RTS athletes and matched healthy athletes. Each physical therapist included one RTS athlete of each of the six most prevalent lower extremity injury types; conservative treated knee injury, surgically treated knee injury, calf injury, hamstring injury, ankle inversion injury, or adductor injury. RTS athletes were all included at the criterion-based point of RTS. The physical therapists gave clearance for RTS according to the definition by Ardern et al37: "Returning to the defined sport, but not performing at the desired performance level" regardless of whether this was based on objective criteria or not.38,39 In order to have a real-life presentation of RTS-decisions in the usual care of physical therapists, the researchers were not involved in the rehabilitation process and RTS decision-making.40 After RTS clearance, RTS athletes were eligible for participation if they met the following criteria: 18-45 years of age and participating at least twice a week in high-impact sports before the injury. A lower extremity injury was considered as a time-loss injury resulting in the athlete not being able to practice their sport for at least one training or match.41 High-impact sports were defined as sports involving jumping, pivoting, and changes of direction. Athletes were excluded if they had a rheumatic or a neurological disease. For each included RTS athlete, a healthy athlete, practicing sport at the desired performance level without injury, was selected and matched by gender, sport, age (range within five years), height (range within 10 centimeters), and dominant leg (the leg used to kick a ball).18,24 Physical therapists recruited healthy athletes via the network in sport clubs or the team or network of the RTS athlete. Healthy athletes were eligible for participation if they met the same criteria as the RTS athletes with the exception of having suffered a lower extremity injury.

HOP TESTS

Five single-legged hop tests were executed according to previously described protocols.18,42–45 The hop tests were the single hop,18,43 triple hop,18,43 crossover hop,18,43 vertical jump,42 and 50 seconds side hop.44,45 Athletes were allowed to use arm swings.18,43,46,47 For the single, triple, and crossover hop, athletes were instructed to hop as far as possible for one jump, three jumps, or three diagonal jumps respectively.18,43 The distance was measured from the toe at the starting position to the toe at the landing position using a standard tape measure.43 For the vertical jump, the athlete was instructed to jump as high as possible with chalk on the tip of the middle finger, where the standing
reach height was subtracted from the total jump height.\textsuperscript{42} For the single hop, triple hop, crossover hop, and vertical jump, athletes were asked to maintain a balanced landing for two seconds.\textsuperscript{18,43} A failed jump involved the loss of balance, touching the floor with the arms or contralateral leg, or using an additional hop on landing.\textsuperscript{43,44,47} Failure resulted in a disqualified hop.\textsuperscript{44} For the 30 seconds side hop the athletes were instructed to jump from side to side, over two strips 40 centimeter apart, as many times as possible in 30 seconds.\textsuperscript{44,45} Number of jumps, without touching the tape or touching the floor with the other foot, was recorded.\textsuperscript{45} For these hop tests, test-retest reliability ranges from 0.80 to 0.97.\textsuperscript{18,43–48}

**PROCEDURES**

Physical therapists received written instructions for the test procedures, execution, and scoring of the hop tests. In addition, physical therapists attended a three-hour practice session and received written instructions for the test procedures (Appendix 1). Before testing, athletes filled out a questionnaire regarding personal characteristics, their injury, and sport participation. A warm-up was carried out before the hop tests, during which the athlete ran for five minutes at a comfortable pace. After the therapist explained and demonstrated the hop test, the athlete practiced the test once.\textsuperscript{43,46,47} Tests were executed three times per leg.\textsuperscript{44–48} Failure to perform an attempt according to the protocol resulted in a disqualified hop.\textsuperscript{44} Besides the given instructions, athletes were not verbally encouraged.\textsuperscript{48} Hop tests were completed wearing sport shoes\textsuperscript{18,43,44,46,47} on a hard, even, and non-slippery surface.\textsuperscript{43,47} The order of hop tests and the leg that started were randomized (random.org).\textsuperscript{44,48} The hop tests were carried out alternately with both legs.\textsuperscript{45–47} Between the three trials of the 30 seconds side hop, athletes could rest for 30 seconds.\textsuperscript{18,43,48}

**STATISTICAL ANALYSIS**

Leg matching was achieved by matching the injured and non-injured leg of the RTS athlete with the corresponding leg of the healthy athlete. The maximum values for both legs were used.\textsuperscript{24,44,46} In case of three disqualified hop tests, the maximum value could not be used. The LSI was calculated by dividing the score of the injured leg or matched leg by the score of the non-injured leg or matched leg multiplied by 100%.\textsuperscript{18,42} Descriptive statistics were calculated to summarize athletes’ characteristics and outcomes of the hop tests. The differences in characteristics between RTS athletes and healthy athletes were analyzed using the McNemar test for dichotomous data and the paired t-test for continuous data.

Test-retest reproducibility using the values of each leg of the hop tests was measured by calculating an Intraclass Correlation Coefficient agreement (ICC\textsubscript{a}) (two-way random effects model, single measure). An ICC above 0.75 represents excellent reproducibility; 0.60-0.74 good reproducibility; 0.40-0.59 fair reproducibility; and <0.40 low reproducibility.\textsuperscript{49}

Differences in paired data regarding hop test outcomes between RTS athletes and healthy athletes were examined for normal distribution. In case of normal distribution, the paired t-test was used to compare differences in hop tests between RTS athletes and healthy athletes. When data were non-normally distributed, the Wilcoxon signed rank test was used. For sensitivity analysis, the before mentioned differences were also analyzed using the mean score of the hop tests, because the mean is also used in clinical practice.\textsuperscript{42,43,46–48}

The Cohens’ d was used to analyze the magnitude of difference with the effect size. The effect size is an objective, standardized, and easy to interpret measure regarding how big the difference is.\textsuperscript{50} An effect size of 0.20-0.49 was considered as small; 0.50-0.79 as medium; and ≥ 0.80 as large.\textsuperscript{50} Statistical significance was set at the $p < 0.05$ level. Statistical Package for the Social Science (IBM SPSS, Chicago, IL, version 25) for Windows was used for statistical analysis. Sample size was calculated using G*Power two-tailed with an alpha of 0.05, a power of 0.95, and a small effect size (0.2), resulting in a required sample size of 327 athletes.

**RESULTS**

**CHARACTERISTICS OF ATHLETES**

One hundred ninety-two RTS athletes were eligible for participation, but 25 were excluded. The excluded RTS athletes were not significantly different from included RTS athletes regarding gender, age, weeks since injury occurrence, and weeks in rehabilitation. Also 23 healthy athletes were excluded, who were not significantly different in gender and age compared to included healthy athletes.

Hop tests were completed by 169 RTS athletes and 169 healthy athletes, both aged 25.8 years ($\pm$ 5.7, 5.6, respectively). Of all participating athletes, 70.4% were male. Among RTS athletes, 28 athletes were surgically treated for knee injuries (16.2%), of which 76% underwent an ACLR. There were 141 athletes conservatively treated, including 29 athletes with knee injuries (17.2%), 28 with calf injuries (16.2%), 28 with hamstring injuries (16.2%), 28 with ankle inversion injuries (16.2%), and 28 with adductor injuries (16.2%). Soccer (61.2%), hockey (10%), handball (7%), and volleyball (6%) were the most prevalent practiced sports. No significant differences were observed between RTS athletes and healthy athletes regarding gender, age, height, dominant leg, number of training sessions, number of matches, minutes training, and minutes matches per week. The percentage of RTS athletes meeting LSI’s $\geq 90\%$ ranged from 61.5% to 81.7%. In the healthy athletes, the percentage of athletes meeting LSI’s $\geq 90\%$ ranged from 71.0% to 91.1% (Table 1).

**TEST-RETEST REPRODUCIBILITY HOP TESTS**

Test-retest reproducibility of the hop tests ranged from ICC\textsubscript{a} 0.87 to ICC\textsubscript{a} 0.94, indicating excellent reproducibility.

**COMPARISONS BETWEEN THE NON-INJURED LEG IN RTS ATHLETES AND THE MATCHED LEG IN HEALTHY ATHLETES**

No significant differences were found between the non-in-
Table 1. Characteristics of RTS athletes and healthy athletes

<table>
<thead>
<tr>
<th></th>
<th>RTS Athletes (n=169)</th>
<th>Healthy athletes (n=169)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males, n (%)</td>
<td>119 (70.4)</td>
<td>119 (70.4)</td>
<td>1.00</td>
</tr>
<tr>
<td>Age (yrs.)</td>
<td>25.8 ± 5.7</td>
<td>25.8 ± 5.6</td>
<td>0.89</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180.4 ± 8.2</td>
<td>180.5 ± 7.8</td>
<td>0.79</td>
</tr>
<tr>
<td>Dominant right leg, n (%)</td>
<td>152 (89.9)</td>
<td>152 (89.9)</td>
<td>1.00</td>
</tr>
<tr>
<td>Number of training sessions per week</td>
<td>3.0 ± 1.6</td>
<td>2.9 ± 1.6</td>
<td>0.80</td>
</tr>
<tr>
<td>Minutes training per week</td>
<td>230.2 ± 119.3</td>
<td>233.5 ± 131.0</td>
<td>0.76</td>
</tr>
<tr>
<td>Number of matches per week</td>
<td>1.0 ± 0.4</td>
<td>1.00 ± 0.4</td>
<td>0.96</td>
</tr>
<tr>
<td>Minutes matches per week</td>
<td>79.2 ± 32.9</td>
<td>80.7 ± 34.7</td>
<td>0.44</td>
</tr>
<tr>
<td>Time since injury occurrence (weeks)</td>
<td>23.2 ± 30.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time in rehabilitation (weeks)</td>
<td>14.9 ± 20.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single hop LSI ≥90, n (%)</td>
<td>138 (81.7) (n=167)</td>
<td>151 (89.3) (n=166)</td>
<td>0.07</td>
</tr>
<tr>
<td>Triple hop LSI ≥90, n (%)</td>
<td>135 (79.9) (n=168)</td>
<td>154 (91.1) (n=166)</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Crossover hop LSI ≥90, n (%)</td>
<td>134 (79.3)</td>
<td>148 (87.6) (n=163)</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Vertical jump LSI ≥90, n (%)</td>
<td>104 (61.5) (n=158)</td>
<td>120 (71.0) (n=161)</td>
<td>0.11</td>
</tr>
<tr>
<td>30 seconds side hop LSI 90, n (%)</td>
<td>125 (74.0)</td>
<td>135 (79.9)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

*±=standard deviation, cm=centimeter, LSI=Limb Symmetry Index, max=maximum, min=minimum, RTS=Return to Sport, yrs.=years, *=significant difference between athletes returning to sport and matched healthy athletes

The non-injured leg can be used as a reference for the injured leg in single-legged hop tests.

COMPARISONS BETWEEN THE INJURED LEG IN RTS ATHLETES AND THE MATCHED LEG IN HEALTHY ATHLETES

For the triple hop, crossover hop, and 30 seconds side hop, a significant difference was found for the injured leg in RTS athletes compared to matched leg of healthy athletes (p<0.01), with effect sizes ranging from 0.23 to 0.28, indicating small effects. On the absolute scores of the injured leg, RTS athletes performed worse on all hop tests compared to the healthy athletes (Table 2).

COMPARISONS OF LSI’S BETWEEN RTS ATHLETES AND HEALTHY ATHLETES

LSI of RTS athletes was significantly lower for the single hop (p=0.01), triple hop (p<0.01), and 30 seconds side hop (p=0.02) compared to LSI of healthy athletes, with effect sizes ranging from 0.19 to 0.26. For the crossover hop and vertical jump, RTS athletes scored lower LSI’s compared to healthy athletes, but these differences were not significant (Table 3).

SENSITIVITY ANALYSIS

When using the mean outcomes of the hop tests instead of the maximum outcomes, RTS athletes also did not perform significantly differently with their non-injured leg compared to the matched leg of healthy athletes (Table 4). In addition, both the outcomes of the injured leg and the LSI were also lower in RTS athletes compared to the matched leg and the LSI of healthy athletes.
Table 2. Comparison of scores on the hop tests of the injured and non-injured leg between RTS athletes and the matched legs in healthy athletes

<table>
<thead>
<tr>
<th>Hop test</th>
<th>RTS athletes (n=169)</th>
<th>Healthy athletes (n=169)</th>
<th>Mean difference ± SD (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single hop</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured or matched leg (cm)</td>
<td>176.9 ± 35.3</td>
<td>181.1 ± 31.7</td>
<td>-4.7 ± 35.2 (-10.1 – 0.7)</td>
<td>0.09</td>
</tr>
<tr>
<td>Mean ± SD 4 missing</td>
<td>2 missing</td>
<td>2 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg(cm)</td>
<td>181.4 ± 33.3</td>
<td>183.2 ± 31.2</td>
<td>-1.8 ± 32.0 (-6.6 – 3.1)</td>
<td>0.48</td>
</tr>
<tr>
<td>Mean ± SD 1 missing</td>
<td>0 missing</td>
<td>1 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Triple hop</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Injured or matched leg (cm)</td>
<td>500.5 ± 92.0</td>
<td>519.7 ± 87.7</td>
<td>-19.1 ± 82.2 (-41.3 – -6.6)*</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Mean ± SD 2 missing</td>
<td>1 missing</td>
<td>2 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg(cm)</td>
<td>517.6 ± 88.6</td>
<td>521.5 ± 85.4</td>
<td>-4.1 ± 79.7 (-16.3 – 8.0)</td>
<td>0.50</td>
</tr>
<tr>
<td>Mean ± SD 2 missing</td>
<td>0 missing</td>
<td>2 missing</td>
<td></td>
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</tr>
<tr>
<td><strong>Crossover hop</strong></td>
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<tr>
<td>Injured or matched leg (cm)</td>
<td>451.0 ± 98.0</td>
<td>477.6 ± 92.5</td>
<td>-26.7 ± 95.4 (-41.3 – -12.2)*</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Mean ± SD 2 missing</td>
<td>1 missing</td>
<td>2 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg(cm)</td>
<td>461.5 ± 98.9</td>
<td>475.1 ± 92.3</td>
<td>-13.3 ± 96.2 (-28.0 – 1.5)</td>
<td>0.08</td>
</tr>
<tr>
<td>Mean ± SD 4 missing</td>
<td>0 missing</td>
<td>4 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vertical jump</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured or matched leg (cm)</td>
<td>23.6 ± 8.0</td>
<td>24.7 ± 7.8</td>
<td>-1.0 ± 8.3 (-2.3 – 0.3)</td>
<td>0.13</td>
</tr>
<tr>
<td>Mean ± SD 12 missing</td>
<td>7 missing</td>
<td>6 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg(cm)</td>
<td>24.6 ± 7.8</td>
<td>25.0 ± 7.8</td>
<td>-0.6 ± 8.8 (-1.9 – 0.8)</td>
<td>0.42</td>
</tr>
<tr>
<td>Mean ± SD 8 missing</td>
<td>4 missing</td>
<td>4 missing</td>
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<tr>
<td><strong>30 seconds side hop</strong></td>
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</tr>
<tr>
<td>Injured or matched leg (x)</td>
<td>47.1 ± 14.6</td>
<td>50.5 ± 14.1</td>
<td>-3.4 ± 13.0 (-5.4 – -1.4)*</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Mean ± SD 0 missing</td>
<td>0 missing</td>
<td>0 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg(x)</td>
<td>48.8 ± 13.9</td>
<td>50.5 ± 14.4</td>
<td>-1.8 ± 12.7 (-3.7 – 0.2)</td>
<td>0.08</td>
</tr>
<tr>
<td>Mean ± SD 0 missing</td>
<td>0 missing</td>
<td>0 missing</td>
<td></td>
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</tbody>
</table>

*significant difference between athletes returning to sport and matched healthy athletes, cm=centimeter, CI=confidence interval, ES=effect size, RTS=Return to Sport, SD=standard deviation, x=number of correct performed jumps

Table 3. Comparison of LSI between RTS athletes and healthy athletes

<table>
<thead>
<tr>
<th>Hop test</th>
<th>RTS athletes (n=169)</th>
<th>Healthy athletes (n=169)</th>
<th>Mean difference ± SD (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single hop</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSI (%) ± SD 5 missing</td>
<td>97.1 ± 10.2</td>
<td>99.5 ± 8.5</td>
<td>-2.5 ± 12.9 (-4.6 – 0.5)*</td>
<td>0.01*</td>
</tr>
<tr>
<td>Mean ± SD 2 missing</td>
<td>2 missing</td>
<td>3 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Triple hop</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSI (%) ± SD 4 missing</td>
<td>96.9 ± 9.2</td>
<td>99.8 ± 7.2</td>
<td>-2.9 ± 11.2 (-4.6 – -1.5)*</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Mean ± SD 1 missing</td>
<td>1 missing</td>
<td>3 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Crossover hop</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSI (%) ± SD 6 missing</td>
<td>98.6 ± 13.5</td>
<td>100.7 ± 8.9</td>
<td>-1.9 ± 15.8 (-4.3 – 0.6)</td>
<td>0.14</td>
</tr>
<tr>
<td>Mean ± SD 11 missing</td>
<td>0 missing</td>
<td>6 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vertical jump</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSI (%) ± SD 17 missing</td>
<td>97.9 ± 20.7</td>
<td>99.9 ± 18.9</td>
<td>-1.8 ± 28.4 (-6.3 – 2.8)</td>
<td>0.45</td>
</tr>
<tr>
<td>Mean ± SD 20 missing</td>
<td>11 missing</td>
<td>8 missing</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>30 seconds side hop</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>LSI (%) ± SD 0 missing</td>
<td>97.2 ± 17.4</td>
<td>101.8 ± 17.2</td>
<td>-4.5 ± 24.2 (-8.2 – -0.9)*</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Mean ± SD 0 missing</td>
<td>0 missing</td>
<td>0 missing</td>
<td></td>
<td></td>
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</tbody>
</table>

*significant difference between athletes returning to sport and matched healthy athletes, CI=confidence interval, ES=effect size, LSI=Limb Symmetry Index, RTS=Return to Sport, SD=standard deviation

DISCUSSION

This study found no differences between the non-injured leg of RTS athletes after lower extremity injury and the matched leg of healthy athletes. This suggests that the non-injured leg could be used as a reference for the injured leg in athletes when deciding on return to high-impact sports. In addition, although RTS athletes performed consistently lower with their injured leg and had a lower LSI compared...
to the matched leg and LSI of healthy athletes, differences were negligible to small.

**THE NON-INJURED LEG AS A REFERENCE FOR THE INJURED LEG IN RTS DECISION-MAKING**

Previous authors studying athletes after ACLR found that performance of both the injured and non-injured leg was significantly lower compared to the matched leg of healthy athletes.\(^{11,23-25,27}\) In these time-based studies, athletes were tested six to nine months after ACLR, with the time frame as main criterion to establish whether an athlete was ready to RTS.\(^{21,51,55}\) However, RTS clearance might have been premature since it has been advised to delay RTS to at least nine months after ACLR.\(^{5,52}\) The 28 RTS athletes in this study after surgically treated knee injuries were 45 weeks (± 20) in rehabilitation. When comparing the hop test outcomes of the non-injured legs with the matched leg of healthy athletes, no significant differences were found with effect sizes ranging from 0.05 to 0.35. This indicates that also after surgically treated knee injuries at the criterion-based point of RTS the non-injured leg could be used as reference for the surgically treated leg, however, the sample size of 28 is too small to make a substantiated statement.

Although athletes after ACLR were able to achieve LSI’s of ≥90 %, they failed to meet normative or pre-injury performance levels.\(^{11,25}\) This raises concerns regarding the value of the LSI in the RTS decision-making process which may contribute to premature or unsuccessful RTS with an increased risk for a second ACLR.\(^{11,19,31}\) In addition, no association was found between passing RTS hop test criteria on the LSI and RTS\(^{21,51,53,54}\) or between passing RTS hop test criteria on the LSI and the risk of a reinjury.\(^{21,51,55}\) These findings also indicate that there is an urgent need to reconsider the use of the LSI as RTS criterion.\(^{55}\) It is recommended that the non-injured leg is tested immediately after the injury for a more relevant benchmark in the athlete-centered approach or, more preferably, that both legs are tested prior to injury in order to be able to compare with the athletes’ own pre-injury scores and not with matched healthy athletes.\(^{31}\) Since pre-injury scores are often not available in clinical practice, using the non-injured leg as reference standard for the injured leg is an alternative in RTS criterion-based decision-making as this study found that the non-injured leg of RTS is not significantly different from the matched leg of healthy athletes.

Despite RTS clearance was given by the physical therapists in this study, RTS athletes not meeting LSI’s of ≥90% on each of the hop tests ranged from 18.5% to 38.5%. This range at the criterion-based point of RTS is consistent with previous studies where athletes 11-38 months after ACLI or six to seven months after ACLR not meeting LSI’s of ≥90% ranged from 19% to 86%.\(^{39,42,44,56-59}\) Also, 8.9% to 29.0% of healthy athletes in this study did not meet LSI’s of ≥90% on the separate hop tests. Previous findings reported that LSI’s of ≥90% were not achieved in 5% to 20% of the healthy athletes.\(^{44,57}\) For healthy athletes, who have no injured and non-injured leg for calculating the LSI, an LSI below 90% or above 110% can be used for asymmetry.\(^{60}\) When using these cut off scores, asymmetry was present in 16.0% to 51.5% of the healthy athletes in the current study in at least one of the hop tests. This high number of healthy athletes failing to reach the LSI of ≥90% and ≤110% also raises the question regarding the use of the LSI in RTS decision-making if there might be different scores for the dominant or non-dominant leg of ≥10%.\(^{21}\) The use of pre-injury hop scores is again recommended to compare with hop scores at the time of RTS.\(^{51}\) However, the non-injured leg can be used as a reference for the injured leg if pre-injury hop scores are not available.

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**Table 4. Comparison of mean scores on the hop tests between the non-injured leg in RTS athletes and the matched leg in healthy athletes**

<table>
<thead>
<tr>
<th>Hop test</th>
<th>RTS athletes (n=169)</th>
<th>Healthy athletes (n=169)</th>
<th>Mean difference ± SD (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single hop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg (cm) Mean ± SD</td>
<td>142.4 ± 49.2</td>
<td>143.8 ± 50.5</td>
<td>-1.4 ± 57.8 (-10.1 – 7.4)</td>
<td>0.76 ES 0.02</td>
</tr>
<tr>
<td>Triple hop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg (cm) Mean ± SD</td>
<td>411.7 ± 136.9</td>
<td>390.9 ± 146.2</td>
<td>20.8 ± 152.3 (-2.3 – 43.9)</td>
<td>0.08 ES 0.14</td>
</tr>
<tr>
<td>Crossover hop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg (cm) Mean ± SD</td>
<td>351.7 ± 133.3</td>
<td>346.0 ± 138.4</td>
<td>5.7 ± 152.2 (-17.4 – 28.8)</td>
<td>0.63 ES 0.04</td>
</tr>
<tr>
<td>Vertical jump</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg (cm) Mean ± SD</td>
<td>18.2 ± 8.7</td>
<td>19.1 ± 9.0</td>
<td>-0.9 ± 9.3 (-2.3 – 0.5)</td>
<td>0.20 ES 0.10</td>
</tr>
<tr>
<td>30 seconds side hop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-injured or matched leg (x) Mean ± SD</td>
<td>45.2 ± 13.8</td>
<td>46.8 ± 14.4</td>
<td>-1.6 ± 12.7 (-3.6 – 0.2)</td>
<td>0.10 ES 0.13</td>
</tr>
</tbody>
</table>

cm=centimeter, CI=confidence interval, ES=effect size, RTS=Return to Sport, SD=standard deviation, x=number of correct performed jumps.
The Non-injured Leg Can Be Used as a Reference for the Injured Leg in Single-legged Hop Tests

In this study, failure to perform an attempt according to the protocol resulted in a disqualified hop and no repeated attempt was allowed due to the time it takes to execute all hop tests three times per leg. On each attempt, 18.2% of the RTS athletes and 18.5% of the healthy athletes had a disqualified hop. In previous studies, maximum or mean values of three attempts or three successful trials have been used to calculate the LSI. In most of the studies, an unsuccessful landing resulted in a repeated trial. Sometimes additional trials were allowed when hop test scores increased or even when the athlete or administrator felt that a better result could be achieved. In these previous studies, it is not described how many trials were conducted before there were enough approved trials. In this study, it is possible that repeated trials increased the hop test outcomes of athletes. It could be questionable that RTS athletes resume to training with one fifth disqualified outcomes. However, healthy athletes had the same amount of disqualified outcomes.

The results of the current study suggest that the non-injured leg can be used as a reference standard for the injured leg independent of using the maximum or mean scores. The percentage of RTS athletes meeting LSI’s ≥90% based on mean scores ranged from 54.4% for the vertical jump to 71.6% for the 30 seconds side hop. The percentage of RTS athletes meeting an LSI of ≥90% is significantly higher for maximum scores than for mean scores in all hop tests except the 30 seconds side hop. Clinicians should keep in mind that passing the LSI of ≥90% is achieved more easily using the maximum score with the possible consequence of too early RTS and a higher risk of reinjury.

LIMITATIONS OF THIS STUDY

This study has three potential limitations. First, there might have been bias in the selection of RTS athletes. Physical therapists were allowed to select athletes, but this was not conducted in a consecutive order or using random sampling. Secondly, RTS athletes could have become familiar with the hop tests during rehabilitation or in RTS-decision making, leading to a possible overestimation of hop test scores for the RTS athletes. Van Melick et al. also reported this limitation that is unavoidable when athletes are in rehabilitation to RTS and the physical therapist regularly evaluates the function. On the other hand, in this study the percentage disqualified hop tests was similar in the RTS athletes (18.2%) and healthy athletes (18.5%). And third, athletes performed one practice trial and three test trials. In previous studies, one to ten practice trials were executed because of the possible learning effect where scores might improve across trials. It is therefore possible that after one practice trial and three test trials the scores may have increased. However, one previous study found that results could also have stabilized after three or four trials. Although in our study, the maximum score is almost always reached in the third trial, the second trial is not significantly higher than the first trial and the third trial is not significantly higher than the second trial.

CLINICAL IMPLICATIONS AND FUTURE RESEARCH

The current findings indicate that the non-injured leg can be used as a reference for the injured leg after lower extremity injury in RTS decision-making. Davies et al. advised to use two hop tests in different planes to detect abnormality in hop test function. By testing in different planes of motion, the clinician can more clearly identify movement deficits, and these can be subsequently developed through targeted training. However, RTS is complex and influenced by more factors than only single-legged hop tests. In addition to the role of hop tests in multidimensional RTS decision-making, psychological factors, sport-specific decision modifiers, and quality of movement are also important. Measuring and possibly treating psychological responses such as fear is recommended before RTS as negative responses are associated with RTS and (re-)injury. The decision for readiness to RTS also depends on type of sport, level of play, position of play, and playing experience. Besides hop distance or height, factors related to neuromuscular control should also be assessed. For further research it is recommended to measure RTS outcomes such as movement quantity and quality.

CONCLUSION

No differences in single-legged hop tests were observed between the non-injured leg of RTS athletes after lower extremity injury and the matched leg of healthy athletes. Since pre-injury scores are often not available in clinical practice, clinicians can use the score of the non-injured leg as a reference for the score of the injured leg in single-legged hop tests for deciding on return to high-impact sports after lower extremity injuries.

ACKNOWLEDGEMENTS

We thank the participating physical therapists for the recruitment of athletes and for collecting the data. We also thank all the athletes who participated in this study.

DECLARATION OF CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest relevant to the content of this manuscript.

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51. Davies WT, Myer GD, Read PJ. Is it time we better understood the tests we are using for return to sport decision making following ACL reconstruction? A critical review of the hop tests. Sports Med. 2020;50(3):485-495. doi:10.1007/s40279-019-01221-7


APPENDIX 1: SINGLE-LEGGED HOP TESTS

SINGLE HOP TEST

**Required material:** Standard tape measure and a bar to lay against the toe at the landing position.

**Instruction:** Stand on one leg with the toe against the starting line. Hop as far as possible for one jump while taking off and landing on the same foot. Maintain a balanced landing for two seconds. No extra hops or touching the floor with the other foot or hand are allowed. You are allowed to use your arms. The test is not accepted if you lose your balance, touch the floor with the arms or other leg, or when you perform and additional hop on landing. A failed jump resulted in a disqualified hop test outcome and no extra trial is allowed.

**Measuring the outcome:** Measure at the toe at the landing position using a standard tape measure and possibly a bar against the toe, rounded to half a centimeter.

TRIPLE HOP TEST

**Required material:** Standard tape measure and a bar to lay against the toe at the landing position.

**Instruction:** Stand on one leg with the toe against the starting line. Hop as far as possible for three jumps in a row while taking off and landing on the same foot. Maintain a balanced landing for two seconds. No extra hops or touching the floor with the other foot or hand are allowed. You are allowed to use your arms. The test is not accepted if you lose your balance, touch the floor with the arms or other leg, or when you perform and additional hop on landing. A failed jump resulted in a disqualified hop test outcome and no extra trial is allowed.

**Measuring the outcome:** Measure at the toe at the landing position using a standard tape measure and possibly a bar against the toe, rounded to half a centimeter.

CROSSOVER HOP TEST

**Required material:** Standard tape measure, a bar to lay against the toe at the landing position, and two lines with 15 centimeters between the ends of the lines.

**Instruction:** Stand on one leg with the toe against the starting line. When the right leg is tested, you start at the right side of the lines. When the left side is tested, you start at the left sides of the lines. Hop three times as far as possible while executing diagonal hop across a 15-centimeter tape on the floor starting with a medial hop, followed by a lateral hop, and finally medial again. Maintain a balanced landing for two seconds. No extra hops or touching the floor with the other foot or hand are allowed. You are allowed to use your arms. The test is not accepted if you lose your balance, touch the floor with the arms or other leg, or when you perform and additional hop on landing. A failed jump resulted in a disqualified hop test outcome and no extra trial is allowed.

**Measuring the outcome:** Measure at the toe at the landing position using a standard tape measure and possibly a bar against the toe, rounded to half a centimeter.

VERTICAL JUMP

**Required material:** Magnesium, dark paper fixed on the wall, standard tape measure.
The Non-injured Leg Can Be Used as a Reference for the Injured Leg in Single-legged Hop Tests

**Beforehand:** The standing reach is recorded using magnesium on the tip of the middle finger.

**Instruction:** Jump as high as possible taking off and landing on the same foot. Maintain a balanced landing for two seconds. No extra hops, touching the floor with the other foot, or touching the wall with the shoulder or hand.
are allowed. You are allowed to use your arms. The test is not accepted if you lose your balance, touch the floor with the other foot, touch the wall with the shoulder or hand, or when you perform and additional hop on landing. A failed jump resulted in a disqualified hop test outcome and no extra trial is allowed.

**Measuring the outcome:** The top of the standing reach height subtracting from the top of the total jump height, rounded to half a centimeter.

### 30 SECONDS SIDE HOP

**Required material:** Stopwatch or timer with 30 seconds and two lines with 40 centimeters between the ends of the lines.

If desired, the trials can be videotaped and viewed after completion.

**Instruction:** When the right leg is tested, you start at the right side of the lines. When the left side is tested, you start at the left sides of the lines. The physical therapist gives the countdown "3, 2, 1, start". Jump as many times as possible in 30 seconds from side to side on the same leg between two lines placed 40 centimeters apart. You are allowed to use your arms. The jump does not count when you touch the tape or touch the floor with the other foot.

**Measuring the outcome:** Number of successful jumps, without touching the tape or touching the floor with the other foot. The failed jumps were also written.

Between the three trials of the 30 seconds side hop, the athlete could rest 30 seconds.
Establishing Normative Values for Inter-Limb Kinetic Symmetry During Landing in Uninjured Adolescent Athletes

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Keywords: anterior cruciate ligament reconstruction, biomechanics, return to sport, sports medicine

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Background

Assessment of inter-limb kinetic symmetry during landing could provide valuable insights when working with athletes who have undergone anterior cruciate ligament reconstruction. However, it is difficult to determine if the asymmetry exhibited by an injured athlete is excessive or within a range that is similar to uninjured athletes, until normative values are established.

Purpose

The purpose of this study was to establish normative values for inter-limb impact force symmetry in uninjured adolescent athletes. In addition, an example is provided of how these normative values could be used to identify athletes who exhibit atypically high levels of asymmetry following anterior cruciate ligament reconstruction.

Study Design

Cross-sectional study

Methods

One hundred and thirty-six uninjured athletes completed drop vertical jumps and countermovement jumps while force plates recorded ground reaction forces. Symmetry indices captured inter-limb symmetry in impact forces during landing for both tasks. These symmetry indices were also combined to create an index that captured symmetry across both tasks. Normative values were established using the uninjured athletes’ data. Eleven athletes who had undergone anterior cruciate ligament reconstruction and been cleared to return to landing and jumping performed the same tasks and their data were compared to the results for the uninjured group.

Results

Measures of central tendency, variability, percentiles, and outliers were calculated/identified based on the uninjured athletes’ symmetry indices. Six of the 11 injured athletes exhibited atypically high symmetry index values.

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Conclusion

The normative values established as part of this study may serve as a basis for identifying athletes who exhibit atypically high levels of inter-limb impact force asymmetry during jumping tasks following anterior cruciate ligament reconstruction.

Level of Evidence

3b

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are common among adolescent athletes.1 Surgical reconstruction of the ACL is recommended for athletes who intend to return to sport.2 Unfortunately, the risk of sustaining another ACL injury is high among adolescent athletes.3 In fact, it has been reported that approximately 25% of adolescent athletes will suffer a second ACL injury in the first year after they return to sport following ACL reconstruction.4 These alarmingly poor outcomes highlight the urgent need to improve rehabilitation and return-to-sport decision making after ACL reconstruction.

Athletes who have undergone ACL reconstruction often demonstrate marked inter-limb asymmetries in impact forces during landing, even after they have returned to sport.5–10 This persistent asymmetry in limb loading may contribute to the relatively high incidence of ACL injuries in athletes who return to sport following ACL reconstruction.11 The typical pattern of asymmetry involves athletes landing with greater loads on their uninjured limb, vs. their limb that underwent ACL reconstruction.12 This apparent shift in loading away from the ACL-reconstructed limb could help to explain why ACL injuries are common for the previously uninjured limb in adolescent athletes following return to sport,12 as higher impact forces during landing correspond with greater ACL loading13,14 and appear to be a risk factor for primary ACL injury.15,16

Considering that athletes often demonstrate persistent inter-limb asymmetries in impact forces, and the potential relevance of these kinetic asymmetries to their risk of a second ACL injury, it seems likely that information regarding inter-limb impact force symmetry would be of value to sports medicine professionals involved in post-operative rehabilitation and return-to-sport decision making.2,12,17,18 Unfortunately, information of this nature is typically not available to clinicians, as the force plate technology required to record ground reaction forces has traditionally been confined to a laboratory setting. However, the development of portable force plate systems that are more conducive to testing outside of a laboratory, may provide opportunities to begin to assess inter-limb kinetic symmetry throughout rehabilitation in order to guide treatment and return-to-sport decision making.

While advances in technology create opportunities to enhance post-operative rehabilitation and return-to-sport testing, there is still the challenge of determining if an athlete has returned to a ‘normal’ level of inter-limb kinetic symmetry, since some degree of inter-limb asymmetry is typically observed, even in uninjured athletes.19,20 This makes it difficult to determine if the asymmetry exhibited by an athlete who has undergone ACL reconstruction is excessive or within a range that is similar to uninjured athletes. The purpose of this study was to establish normative values for inter-limb impact force symmetry in uninjured adolescent athletes. An example is also provided of how a clinical team could use these normative values to identify athletes who exhibit atypically high levels of asymmetry following ACL reconstruction.

METHODS

One hundred thirty-six (86 males, 50 females) uninjured competitive adolescent athletes and 11 competitive adolescent athletes (6 males, 5 females) who had recently undergone ACL reconstruction (ACLR group) participated in this cross-sectional study. The uninjured athletes’ data were used to establish normative values, while the data from the athletes who had undergone ACL reconstruction were used to provide an example of how a clinical team could use these normative values to identify athletes who exhibit an atypically high level of asymmetry. All athletes were between 14–18 years of age and competed at the high school level. Athletes in the uninjured group needed to have competed in sports that involve frequent landing, jumping, and cutting within the prior year and not have a history of significant lower extremity injury or surgery, or an injury in the previous six months that limited their ability to train or compete. Athletes in the ACLR group needed to have undergone successful unilateral ACL reconstruction within the previous 18 months, completed conventional post-operative rehabilitation, and been cleared to resume landing and jumping activities. Athletes were excluded from the ACLR group if they had a history of significant injury in their uninjured limb. The ACLR group’s data was collected at the time of their return-to-sport testing session. The median number of days since their ACL reconstruction at the time of testing was 191 days (range: 162 to 237 days), which appears to be consistent with the typical timing of return-to-sport testing.21 Ten athletes in the ACLR group had received bone-patellar tendon-bone autografts, while one had received a hamstrings tendon autograft. Six athletes in the ACLR group had suffered a concomitant injury to their meniscus, while five sustained isolated ACL injuries. The athletes in the uninjured and ACLR groups competed in basketball, football, rugby, soccer, tennis, and/or volleyball. Table 1 includes demographic information for the athletes. All athletes provided informed consent or assent prior to enrollment, and a parent or guardian provided consent for athletes younger than 18 years of age. This study was approved by the Lutheran Hospital Institutional Review Board.

All athletes completed the same testing protocol. After a standardized warm-up, athletes performed drop vertical
jumps (DVJs) and countermovement jumps (CMJs) while two adjacent portable force plates simultaneously recorded three-dimensional ground reaction forces at 600 Hz (AccuPower, Advanced Mechanical Technology, Inc., Watertown, MA, USA). These force plates are designed for testing outside of the laboratory setting. For the DVJ task, the athletes dropped from a 31 cm high plyometric box, landed with their feet on separate force plates (initial landing), immediately performed a maximal vertical jump, and landed again. For the CMJ task, the athletes performed a quick squat (countermovement), followed by a maximal vertical jump, and then landed with their feet on separate force plates. Foot position was monitored visually by an investigator during testing and trials were re-collected if an athlete's feet did not appear to contact separate force plates. Athletes were encouraged to focus on jumping as high as possible during performance of the tasks. Arm movement was not restricted for either task. The DVJ and CMJ tasks were analyzed because they are both commonly used for ACL injury risk screening and to evaluate inter-limb symmetry in athletes post-ACLR. Athletes performed four trials for each task; however, only the final three trials were analyzed. The first trial was included to allow athletes to become accustomed to the tasks and/or be cued to correct their technique. The order of the DVJ and CMJ tasks was randomized. Athletes were given a 10 second rest period between trials. Athletes wore their own footwear and athletic apparel during testing.

The ground reaction force data from each force plate were filtered using a 4th order, zero lag, recursive Butterworth filter with a cutoff frequency of 50 Hz. Peak vertical ground reaction forces (‘impact forces’) were identified from each force plate during the initial landing phase. The initial landing phase was defined as the initial 150 ms after athletes contacted each respective force plate during landing. Initial contact was defined as the frame where the vertical ground reaction force first exceeded a threshold of 10 N. Inter-limb impact force symmetry was captured for each trial via a symmetry index (SI), which was calculated by finding the absolute percent difference in impact forces between the limbs using Equation 1, where Xright represents the impact force from the force plate contacted by the right foot and Xleft represents the impact force from the force plate contacted by the left foot.

\[
SI(\%) = 100 \times \frac{|X_{right} - X_{left}|}{0.5 \times (X_{right} + X_{left})}
\]  
(1)

Since this SI captures the absolute difference between the limbs, a value of 0% reflects perfect symmetry in limb loading, while higher values correspond with greater inter-limb asymmetry. Although this SI does not provide information about the direction of asymmetry (i.e. which limb is being loaded more during a trial), the absolute differences between the limbs were analyzed to prevent positive and negative SI values from canceling each other out when averaged. All preliminary data processing was completed via a custom MATLAB script (The MathWorks Inc., Natick, MA, USA).

The three-trial average of the SIs from the DVJ task and CMJ task were calculated for each athlete. While the primary objective of this study was to establish normative values for the individual tasks, the SI values were also combined into a novel metric that captures inter-limb symmetry across both tasks. To create this metric, the SI values from the DVJ task (SI\text{DVJ}) and CMJ task (SI\text{CMJ}) were plotted onto a plane where the origin represented perfect inter-limb symmetry for both tasks (0%, 0%), the SI\text{DVJ} values were on the horizontal axis, and the SI\text{CMJ} values were on the vertical axis. For each point on the coordinate system, the resultant vector from the origin (SI\text{DVJ+CMJ}) was calculated using Equation 2 (Figure 1). This vector (SI\text{DVJ+CMJ}) reflects the combined degree of asymmetry across both tasks.

\[
SI_{DVJ+CMJ}(\%) = \sqrt{SI_{DVJ}^2 + SI_{CMJ}^2}
\]  
(2)

Normative values were established for the SI\text{DVJ}, SI\text{CMJ}, and SI\text{DVJ+CMJ} variables. For each SI, the mean, standard deviation, minimum value, first quartile (Q1), median, third quartile (Q3), maximum value, 50th percentile, 75th percentile, 85th percentile, and 95th percentile were calculated/identified. In addition, threshold values (‘fences’) were established based on the inter-quartile range (IQR) for each of the distributions in order to identify SI values that would be considered ‘outliers’ (Equation 3) and ‘extreme outliers’ (Equation 4) in the distribution of observations for

| Table 1: Demographic information for the uninjured athletes (Uninjured group) and the athletes who had undergone ACL reconstruction (ACLR group). |
|---------------------------------|-----------------|-----------------|
|                                | Uninjured group | ACLR group      |
|                                | (n = 136)       | (n = 11)        |
| Sex (male / female)            | 86 / 50         | 6 / 5           |
| Age (years)                    | 16.3 ± 0.9      | 16.5 ± 0.9      |
| Mass (kg)                      | 71.4 ± 14.2     | 76.9 ± 10.9     |
| Height (m)                     | 1.74 ± 0.10     | 1.77 ± 0.10     |
| Mean ± standard deviation      |                 |                 |
the uninjured athletes.

\[
Outlier\ (\%) = Q3 + 1.5 \times IQR
\]

\[
Extreme\ Outlier\ (\%) = Q3 + 3 \times IQR
\]

This approach is commonly used to identify outliers in a distribution26 and can help to determine the threshold values that reflect mildly atypical (outlier) and extremely atypical (extreme outlier) performance (Figure 2). Data analysis was performed using R software (The R Foundation, Vienna, AUT).

A secondary objective of this study was to provide an example of how these normative values could be used to identify athletes who exhibit atypically high levels of inter-limb asymmetry following ACL reconstruction. When examining inter-limb impact force symmetry in injured athletes, an initial screening can be conducted to determine if an athlete exhibits asymmetry that exceeds what is typically observed in uninjured athletes. Then each trial can explored in order to determine if there is a consistent pattern to the asymmetry (i.e. an athlete consistently placing greater load on a specific limb vs. more random trial-to-trial variation in the limb experiencing greater loading). This information can then be shared among the members of a clinical team (physical therapist, strength and conditioning specialist, surgeon) so that they can consider it when making rehabilitation and return-to-sport decisions. For this study, the SI_{DVJ+CMJ} values for the athletes in the ACLR group were initially examined to determine where they fell within the distribution of SI values based on the uninjured athletes’ data. Athletes in the ACLR group who exceeded the 75th percentile were considered to be exhibiting atypically high levels of inter-limb asymmetry. For the athletes identified as 'atypical', the impact forces for the uninvolved and ACL-reconstructed limbs were examined for each trial in order to determine which limb was being loaded more during the landings, since the SI values are absolute values and only reflect the magnitude of asymmetry. It should be noted that clinicians could certainly use different cutoff points to identify athletes who exhibit varying levels of asymmetry. For instance, the 85th percentile could be used as the cutoff for identifying athletes exhibiting atypically high levels of asymmetry, instead of the 75th percentile. Using the 85th percentile would essentially result in a less stringent cutoff, as asymmetry, instead of the 75th percentile. Using the 85th for identifying athletes exhibiting atypically high levels of asymmetry. For clinicians could certainly use different cutoff points to identify athletes who exhibit varying levels of asymmetry. It should be noted that landings, since the SI values are absolute values and only to determine which limb was being loaded more during the reconstructed limbs were examined for each trial in order 'atypical', the impact forces for the uninvolved and ACL- for the athletes identified levels of inter-limb asymmetry. For the athletes in the ACLR group who exceeded the 75th percentile were considered to be exhibiting atypically high levels of inter-limb asymmetry. The difference between the first (Q1) and third quartile (Q3) is the inter-quartile range (IQR).

where fewer athletes are essentially 'flagged' as exhibiting atypically high levels of asymmetry.

RESULTS

Table 2 includes descriptive statistics and Table 3 includes percentiles and thresholds for the outliers and extreme outliers for each of the symmetry indices. Figure 3 includes histograms for each of the symmetry indices. For the uninjured athletes, the means (± standard deviations) for the SI_{DVJ} and SI_{CMJ} metrics were 16.4 ± 10.3% and 20.2 ± 10.2%, respectively. Indicating that, on average, uninjured athletes demonstrated inter-limb impact force asymmetries of approximately 16-20%.

Table 4 includes the three-trial mean SI_{DVJ} and SI_{CMJ} values for each athlete in the ACLR group (ranked in descending order based on their SI_{DVJ+CMJ} values), as well as the SI values for each trial (+/- signs used to denote which limb experienced greater loading). Six of the 11 athletes exhibited SI_{DVJ+CMJ} Values that were considered atypically high (>75th percentile - 54.6%) based on the threshold used for this study. In each case, it appeared that the atypical degree of inter-limb asymmetry was the result of the athlete landing with greater impact forces on their uninjured limb, vs. their ACL-reconstructed limb, during performance
Table 3: Percentiles, outliers, and extreme outliers for the symmetry indices generated using the uninjured athletes’ data.

<table>
<thead>
<tr>
<th>Percentile Values</th>
<th>50th</th>
<th>75th</th>
<th>85th</th>
<th>95th</th>
<th>Outlier</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{DVJ}$ (%)</td>
<td>14.4</td>
<td>22.4</td>
<td>29.0</td>
<td>40.1</td>
<td>37.3</td>
<td>54.4</td>
</tr>
<tr>
<td>$S_{CMJ}$ (%)</td>
<td>19.2</td>
<td>27.1</td>
<td>31.9</td>
<td>38.0</td>
<td>49.1</td>
<td>71.3</td>
</tr>
<tr>
<td>$S_{DVJ+CMJ}$ (%)</td>
<td>26.5</td>
<td>34.6</td>
<td>41.5</td>
<td>50.4</td>
<td>55.2</td>
<td>76.2</td>
</tr>
</tbody>
</table>

$S_{DVJ} =$ symmetry index - drop vertical jump task  
$S_{CMJ} =$ symmetry index - countermovement jump task  
$S_{DVJ+CMJ} =$ symmetry index - combined symmetry across both tasks  
Extreme $=$ extreme outlier

Table 4: Symmetry index values for athletes in the ACLR group. Values ranked in descending order based on combined symmetry index magnitude ($S_{DVJ+CMJ}$). Values above horizontal line represent athletes whose combined symmetry index was considered atypically high (>75th percentile).

<table>
<thead>
<tr>
<th>Symmetry Index Drop Vertical Jump</th>
<th>Symmetry Index Countermovement Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean SI</td>
<td>%tile</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>$S_{DVJ+CMJ}$</td>
<td>62.0%</td>
</tr>
<tr>
<td>57.8%</td>
<td>53.9%</td>
</tr>
<tr>
<td>45.3%</td>
<td>38.2%</td>
</tr>
<tr>
<td>45.0%</td>
<td>31.4%</td>
</tr>
<tr>
<td>41.0%</td>
<td>40.0%</td>
</tr>
</tbody>
</table>

$S_{DVJ+CMJ} =$ combined symmetry index values  
Mean SI = three-trial mean symmetry index values  
Percentile (%tile) column indicates how athletes would be categorized based on normative values  
* denotes that athlete is considered an outlier  
Grey shading/bold denotes that athlete’s symmetry index value is >75th percentile for specific task  
Trial 1-3 columns include symmetry index values for each trial  
+ reflects greater loading for uninvolved limb, - reflects greater loading for ACL-reconstructed limb

of the CMJ task and/or DMJ task (based on analysis of the symmetry indices from each trial) (Table 4).

DISCUSSION

The purpose of this study was to establish normative values for inter-limb impact force symmetry in uninjured adolescent athletes as they performed landing/jumping tasks that are commonly used for ACL injury risk screening. In addition, an example was provided of how clinicians could use these types of normative values to identify athletes who are exhibiting an atypically high level of asymmetry following ACL reconstruction.

From a clinical perspective, it is important to consider how the ability to identify athletes who are exhibiting an atypically high level of inter-limb impact force asymmetry could be used to guide rehabilitation. It appears that ath-
Although it was not a primary purpose of this study, it was tries (thus creating a mean difference between the limbs).

As a result, it may be critical for sports medicine professionals to develop more targeted intervention strategies to address these factors. This type of targeted assessment/intervention is difficult when normative data is not available. The development of normative values for inter-limb impact force symmetry could also allow clinicians to establish rehabilitation goals for their patients. For instance, a reasonable goal for an injured athlete may be to exhibit asymmetry that is comparable to uninjured athletes. Again, this type of application is challenging unless normative values have been established.

Establishing normative values for inter-limb impact force symmetry could also facilitate the development of more comprehensive return-to-sport testing, where the degree of side-to-side asymmetry in limb loading is considered. At this time, decisions regarding an athlete’s readiness to return to sport are typically based on the time since surgery, knee motion/strength, self-reported knee function, and/or performance on various clinical assessments of sport-related knee function. Information of this nature can be readily collected during a clinical examination; however, a recent meta-analysis found that athletes who meet conventional return-to-sport testing criteria are at similar risk for sustaining a second ACL injury, compared to athletes who fail to meet these criteria. This appears to indicate that information collected during conventional return-to-sport testing may provide limited insight into an athlete’s readiness to safely resume sports participation. As a result, it may be critical for sports medicine professionals to continue to explore novel ways to evaluate readiness to return to sport following ACL reconstruction. Perhaps the ability to identify athletes who exhibit an atypically high level of inter-limb impact force asymmetry could augment conventional return-to-sport testing.

Future studies could also use the normative values provided in this study to examine the proportion of adolescent athletes who exhibit atypically high levels of inter-limb impact force asymmetry following ACL reconstruction. While previous studies have found that, in general, athletes tend to offload their ACL-reconstructed limb during landing, these studies have examined average performance across all subjects. What this type of analysis does not provide, is an indication of whether inter-limb differences are the result of most athletes exhibiting inter-limb asymmetries or only a few athletes exhibiting marked inter-limb asymmetries (thus creating a mean difference between the limbs). Although it was not a primary purpose of this study, it was interesting to note that six of the 11 athletes examined as part of ACLR group exhibited atypically high levels of inter-limb impact force asymmetry across both tasks (SI_DVJ-CMJ >75th percentile). In each of these six cases, the athlete tended to offload their ACL-reconstructed limb. This appears to indicate that inter-limb asymmetries may be quite pervasive in athletes who have undergone ACL reconstruction; however, examination of a larger sample is certainly warranted.

While the results of this study may be of value to clinicians involved in rehabilitation and return-to-sport decision making, there are limitations that should be considered. First, at this time, most clinics do not have access to a portable or laboratory-based force plate system with the specifications (e.g. sensor range, sampling rate) or durability needed for assessment of dynamic tasks such as landing and jumping. However, it is likely that force plate systems will become more commonly used to assess landing/jumping mechanics in clinical settings as their clinical utility continues to be established. Also, only inter-limb symmetry in peak vertical ground reaction forces were examined. Additional insight could be gained from looking at joint-specific loading patterns (e.g. net joint moments or power), which requires data from a motion capture system that incorporates kinematic data. However, impact force symmetry during landing appears to be strongly related to knee joint kinetic symmetry in both uninjured athletes and athletes who have undergone ACL reconstruction. As a result,
assessment of impact force symmetry may provide an indication of asymmetries proximally in the kinetic chain. In addition to loading, it is also critical to highlight the importance of assessing movement quality during testing, since this may also influence ACL injury risk. Finally, it is important to note that there are no well-established thresholds based on inter-limb impact force symmetry for determining if it is safe for an athlete to return to sport. A reasonable goal may be to return injured athletes to a level of symmetry that is comparable to what is observed in most uninjured athletes. However, at this time, it is impossible to determine if this will reduce their risk of re-injury or minimize long-term deficits in knee function. At this point, assessment of inter-limb impact force symmetry would simply provide another piece of information that could be considered when rehabilitating athletes. Although not a limitation to the primary purpose of this study, the amount of trial-to-trial variability in the SI values exhibited by some of the athletes in the ACLR group was notable (Table 4). Perhaps this high degree of variability reflects a relatively unstable motor pattern, which still needs to be refined. Variability in motor performance following ACL reconstruction should continue to be examined.

CONCLUSION

The normative values for landing forces during jumping tasks established as part of this study may serve as a basis for identifying adolescent athletes who exhibit an atypically high level of inter-limb impact force asymmetry following ACLR. It is possible that this type of assessment of inter-limb kinetic symmetry could help to improve rehabilitation and return-to-sport decision making for adolescent athletes.

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Effect of Increasing Running Cadence on Peak Impact Force in an Outdoor Environment

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Keywords: step rate, feedback, injury, kinetics, auditory cueing

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Background
An estimated 56% of recreational runners sustain a running-related injury related to the high impact forces in running. Increasing step frequency (cadence) while maintaining a consistent speed has been shown to be an effective way to lower impact forces which may reduce injury risk.

Purpose
To examine effects of increased cadence on peak impact force during running in an outdoor setting. It was hypothesized that as cadence increases, peak force would decrease.

Study Design
Repeated measures, quasi-experimental

Methods
Peak force and cadence measurements were collected from 15 recreational runners (8 females, 7 males) during two 2.4-mile outdoor runs. Peak force was measured using an insole-based load measuring device. Baseline session run was completed at participant’s naturally preferred cadence and cadence session run was completed at a cadence targeted to be 10% greater than baseline. Pace was monitored with a GPS watch. Cadence was cued by an auditory metronome and measured with both GPS watch and insoles. Repeated-measures ANOVA’s examined the differences in average peak force, GPS-reported cadence, and insole-reported cadence between mile 1 and mile 2, and across the two cadence conditions.

Results
Cadence differences of 7.3% were observed between baseline and cadence sessions (p<0.001). A concurrent decrease in average peak force of 5.6% was demonstrated during the cadence run (p<0.05). Average cadences measured by GPS watch and insoles were found to be the same at both baseline (p=0.096) and during cadence (p=0.352) sessions.

Conclusion
Increasing cadence by an average of 7% in an outdoor setting resulted in a decrease in peak force at two different time points during a 2.4-mile run. Furthermore, using a metronome for in-field cadence manipulation led to a change in cadence. This suggests that a metronome may be an effective tool to manipulate cadence for the purpose of decreasing peak impact force in an outdoor setting.
Effect of Increasing Running Cadence on Peak Impact Force in an Outdoor Environment

Level of evidence

3b

INTRODUCTION

Within the U.S., the number of people running for exercise has dramatically increased over the past couple of decades. In 1990, five million people annually were reported to complete a road race. Nearly 30 years later, that number has reported to be 17.9 million. While this increase in recreational running has obvious health and wellness benefits for the general population, the relative risk of sustaining a running-related injury (RRI) should be considered. Lower extremity RRIs occur in an estimated 56% of recreational runners, with some suggesting this to be as high as 80%. Since RRIs are so prevalent, it is important to consider which factors may influence risk. While there have been a variety of proposed mechanisms for RRIs, high impact loading is often considered to be a factor. Davis, Bowser and Mullineaux examined 240 runners over a two-year period and reported that impact loads were greater in those runners who experienced an RRI compared to non-injured runners. They subsequently recommended that interventions aimed at decreasing the impact loads may be an effective strategy for reducing injury. In a systematic review by van der Worp, Vrielink and Bredeweg, studies were reviewed and showed that runners with higher loading rates were more likely to have injuries than those with lower rates.

Impact loads may play a large role in many RRIs; therefore, many clinicians and researchers have shifted their focus to remedies for reducing impact and loading rate as a form of injury prevention or to assist in return to running following injury. One method to alter such impact forces is to increase cadence. Increasing cadence while maintaining a consistent pace has been reported to be an effective way to immediately lower impact, thus reducing injury risk.

Many studies to date have primarily been conducted in a controlled, laboratory setting utilizing motorized treadmills. While treadmills have been shown to produce biomechanically similar running patterns, they have the potential for changing spatiotemporal patterns. Tao, et al. reported an increased cadence, and decreased stance and swing time duration, when running on a level or inclined treadmill compared to running outdoors. In addition, outdoor running may produce notable variations in pace, cadence, and/or stride length during distance running events, as opposed to the constant pace imposed by the use of a treadmill. Therefore, to examine the efficacy of cadence manipulation used for recreational running in an etiologically valid scenario, how cadence influences impact forces should be evaluated within a natural outdoor running environment.

To produce a change in spatiotemporal gait parameters, a runner will require a feedback strategy to prompt an increase in cadence. The methods for administering such feedback include the use of concurrent (provided during a task) and terminal (provided at conclusion of task) feedback. According to Broker, et al., concurrent feedback is most effective for cyclical activities such as running and cycling. Such feedback, when provided in an auditory manner, produces the most desirable change in performance when provided immediately after the same event in each cycle of movement. In other words, to promote immediate change in running performance, an auditory stimulus should be given for each step taken. Additionally, alternative forms of concurrent feedback such as a visual stimulus are not feasible to provide to a runner in an open, outdoor environment. Previous studies utilizing an audio metronome in a laboratory environment have demonstrated changes to cadence in runners with the use of an external auditory cue. This simple feedback cue would be compatible for delivery by a wearable portable device such as a watch or smartphone used outdoors.

The purpose of this study was to examine the effects of increased cadence on peak impact force in an outdoor setting. It was hypothesized that an increased cadence would decrease peak ground reaction force. A secondary aim of this study was to explore the feasibility of using an auditory metronome as a stimulus cue to increase cadence during an outdoor run.

METHODS

STUDY DESIGN

This study utilized a repeated measures design, conducted on 15 recreational runners. Data were collected over a period of five weeks. The study protocol was approved by the University of Wisconsin-La Crosse Institutional Review Board and all participants provided informed consent prior to participation.

PARTICIPANTS

Fifteen male and female adult recreational runners were recruited for the study using convenience sampling of university students. Participants were recreational runners that ran an average of 14.8 ± 8.4 miles/week. The study excluded participants who reported a lower extremity injury in the prior three months, a history of lower extremity surgery, current lower extremity pain during running, or presence of a medical pathology that would cause difficulty running for up to one hour.

INSTRUMENTS

Loadsol insole sensors (novel gmbh, Munich, Germany) were placed inside each participant’s typical running shoes bilaterally to measure peak force in Newtons (N). Peak force data were collected at 100 Hz and transmitted through Bluetooth connection to a 6th generation iPod Touch (Apple, California, USA) using the pedoped Loadsol application (Version 1.4.72, novel gmbh, Munich, Germany). The Loadsol insoles have been shown to yield comparable peak force data compared to an instrumented treadmill for running (ICCs: 0.78-0.92) and reliable between sessions (ICCs: 0.88-0.95). Burns, et al. showed equally compelling data in support of Loadsol use to measure ground reaction forces

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by comparisons to hopping, walking and running on a force platform and an instrumented treadmill.

A Garmin Forerunner 25 GPS watch with Garmin Connect app (Version 4.5.1, Garmin International Inc., Olathe, KS) was used to determine running pace and cadence. Similar types of Garmin watches with GPS technology were validated as a measure of distance (absolute percent error: 0.74%) and as a reliable measure of cadence (ICC: 0.95).18,19

The MetroTimer app (Version 3.3.2, ONYX Apps, United States) was used on the iPod Touch to provide auditory cadence cueing. Body mass measurements were taken using a digital scale.

PROCEDURE

Participants completed a questionnaire to collect training/injury history and were then weighed. Participants were given up to 10 minutes to perform their self-selected warm up routine consisting of stretching and a short run no more than 0.25 mile. Following this warm up, Loadsol sensor insoles, GPS watch, and running belt containing iPod Touch were fitted for the participant. Loadsol sensor insoles were placed bilaterally in each participant’s typical running shoes and then calibrated following the manufacturer’s guidelines using the Loadsol application on the iPod touch. Calibration was completed following the procedure previously outlined by Peebles, et al.20 A quarter mile, warm up jog was then conducted to provide acclimation to this equipment.

Participants completed two separate 2.4-mile distance runs (“baseline” and “cadence” sessions) approximately one week apart. The selected road course was a straight stretch void of turns, with minimal elevation change (<20 feet), and minimal traffic. During a single run, participants ran 1.2 miles out, immediately turned around, and completed the same distance back to the starting point. This minimized the amount of turns on the straight, flat road available. The 2.4 mile distance was chosen for the run to allow for a comparison of miles 1 and 2 over time and to accommodate the acceleration up to a steady pace and acclimation to the auditory metronome cues.

For the baseline session, participants were instructed to run at a consistent, self-selected comfortable pace that they could maintain for up to an hour. The metronome was turned off for this run and no mention of running cadence was given to ensure that the run was completed at their typical cadence. Participants were given a GPS watch to monitor pace during this run. After the baseline session completion, cadence and pace data were gathered from the GPS watch to be utilized for setting up parameters for the cadence session scenario on a different day. Cadence and peak force data were collected from insoles. Based on previous treadmill cadence research, a 10% increase in cadence over individual baselines was used as the target for the cadence session scenario.6,7

The cadence session was conducted within ten days of the baseline session to decrease the potential for training or fatigue effects. Participants were told to continue their normal training regimen between these sessions. Shoes, warm up time, and calibration procedures were consistent with their baseline session. The 10% increase in cadence was implemented using the MetroTimer metronome app on iPod Touch for the duration of the cadence session without an earbud or headphone on a quiet running course. Participants were reminded of their baseline pace and instructed to maintain that pace with use of GPS watch while also maintaining target cadence based on the metronome audio cues. A quarter mile jog was again provided to allow acclimation to the running pace and metronome cadence before beginning the session. Cadence was measured via both GPS watch and Loadsol insoles and examined at a later date.

DATA MANAGEMENT AND ANALYSIS

Peak force data were extracted from 20 right foot steps surrounding each quarter-mile increment and averaged, producing a total of eight force time series curves of the right stance phase during each run. Cadence was determined from insole data by obtaining right insole the peak-to-peak timing of the vGRF over the 20 steps for each quarter-mile increment and was reported as steps/minute (SPM). Since cadence is based typically on right and left foot contacts and only the right foot data were extracted for analysis, these times were divided by 2. Similarly, peak forces were expressed in body weight (BW) for only these right steps. Peak force and insole cadence data were collapsed to an average over mile 1 and mile 2 separately for both baseline and cadence sessions. These data were analyzed in IBM SPSS Statistics version 25 (Armonk, NY, USA). To examine differences in average peak force, a repeated measures 2x2 ANOVA was performed on session (baseline, cadence sessions) and distance (mile 1, mile 2) (alpha was set to 0.05). An additional 2x2 ANOVA was performed on session (baseline, cadence sessions) and distance (mile 1, mile 2) variables to examine differences in insole-reported cadence. A third repeated measures ANOVA was performed on session (baseline, cadence sessions) and device (Insoles, GPS watch) to identify any differences between the two devices. Post hoc testing was performed using Bonferroni correction.

RESULTS

Fifteen participants (8 females, 7 males) with a mean age of 23.5 years (range 22-26) completed both baseline and cadence sessions. The reported average weekly mileage was 16.5 miles. A repeated measures ANOVA revealed a 5.6% decrease in average peak force after cadence manipulation when compared to baseline (p<0.05) (Figure 1). Peak force decreases were found to have medium effect size (Cohen’s d=0.56) (Table 1). During both the baseline and cadence session runs there was no difference in peak force during the first mile compared to the second mile (p=0.202) and no interaction effect found between session and distance (p=0.13).

Mean and 95% Confidence Intervals for average cadence expressed in steps per minute (SPM) on one lower extremity throughout Mile 1 and Mile 2 for both Baseline and Cadence Tests during outdoor running.

Results from the two-way ANOVA demonstrated insole-measured cadence increased 7.3% from baseline to cadence sessions (p<0.001) (Figure 2). The effect size for the cadence increase was high (Cohen’s d=1.24) (Table 2). Average ca-
Table 1. Descriptive Statistics and ANOVA results for Insole-measured Cadence

<table>
<thead>
<tr>
<th></th>
<th>Mean (SPM)</th>
<th>SD (SPM)</th>
<th>p-value</th>
<th>Effect Size (Cohen’s d)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline test</td>
<td>82.94</td>
<td>4.4</td>
<td>0.000</td>
<td>1.24</td>
</tr>
<tr>
<td>Cadence test</td>
<td>89.03</td>
<td>4.33</td>
<td>0.799</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Distance</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mile 1</td>
<td>86.27</td>
<td>4.26</td>
<td>0.032</td>
<td>0.13</td>
</tr>
<tr>
<td>Mile 2</td>
<td>85.71</td>
<td>4.34</td>
<td>0.597</td>
<td>0.14</td>
</tr>
</tbody>
</table>

SPM= unilateral steps per minute

dence was found to decrease from mile 1 to mile 2 by 0.56 steps per minute (p=0.032). However, there was no interaction effect found between session and distance (p=0.597).

Mean and 95% Confidence Intervals for peak vertical ground reaction force (vGRF) expressed in multiples of bodyweight (BW) between Mile 1 and Mile 2 for Baseline and Cadence Tests during outdoor running.

When comparing the average cadence measured by the insoles against the cadence measured by the GPS watch, the two-way ANOVA results revealed no difference in measurement between the devices (p=0.096), yet an overall increase in average cadence remained between sessions (p=0.001), confirming that both devices were able to detect a similar percent change in cadence from baseline to cadence sessions (Figure 3) (Table 3). No interaction effect was determined between session and distance (p=0.928).

Mean and 95% Confidence Intervals for average cadence expressed in steps per minute (SPM) on one lower extremity throughout Baseline and Cadence Tests. Data compared cadence measured between Garmin GPS watch (Watch) and Loadsol insole sensors (Insole) during outdoor running.

**DISCUSSION**

The purpose of this study was twofold: 1) to determine the effect of cadence modification on peak impact force during an outdoor run, and 2) to examine the immediate response and magnitude of cadence modification through the use of a metronome as an auditory stimulus during a second session. It was hypothesized that as cadence increased, peak impact forces would decrease. It was additionally hypothesized that use of a metronome would produce a higher cadence during the run.

In support of these hypotheses, participants demonstrated a substantial increase in cadence by 7.3% using a metronome for outdoor running with a concurrent decrease in average peak impact force by 5.6%. One possible explanation for this change in lower extremity impact could be due to a change in foot strike pattern that may occur from the manipulation of the spatiotemporal factors associated with gait, however this was not directly measured or quantified. Increasing cadence has been shown to promote a change from a rearfoot strike pattern to a mid- or forefoot strike, which may result in decreased vertical loading between 0.3-1.3 body weights (BW).21,22 A change from rearfoot to forefoot strike may have other beneficial effects including decreasing knee joint contact forces by an average of 27%.24 However, a forefoot strike may increase stress and loading at the Achilles tendon, ankle, and plantar...
Table 2. Descriptive Statistics and ANOVA results for Peak GRF

<table>
<thead>
<tr>
<th></th>
<th>Mean (BW)</th>
<th>SD (BW)</th>
<th>p-value</th>
<th>Effect Size (Cohen’s d)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline test</td>
<td>2.539</td>
<td>0.267</td>
<td>0.029</td>
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<tr>
<td>Cadence test</td>
<td>2.396</td>
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<td></td>
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<tr>
<td><strong>Distance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mile 1</td>
<td>2.484</td>
<td>0.222</td>
<td>0.202</td>
<td>0.146</td>
</tr>
<tr>
<td>Mile 2</td>
<td>2.451</td>
<td>0.229</td>
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<td></td>
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</tbody>
</table>

GRF = ground reaction force, BW= peak force normalized by multiples of individual body weight

Table 3. Descriptive Statistics and ANOVA results for Cadence between GPS and Insole

<table>
<thead>
<tr>
<th></th>
<th>Mean (SPM)</th>
<th>SD (SPM)</th>
<th>p-value</th>
<th>Effect Size (Cohen’s d)</th>
</tr>
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<tbody>
<tr>
<td><strong>Time</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Baseline test</td>
<td>82.75</td>
<td>4.35</td>
<td>0.000</td>
<td>1.43</td>
</tr>
<tr>
<td>Cadence test</td>
<td>88.81</td>
<td>4.11</td>
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<tr>
<td><strong>Device</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insole</td>
<td>85.99</td>
<td>4.28</td>
<td>0.067</td>
<td>0.08</td>
</tr>
<tr>
<td>Watch</td>
<td>85.57</td>
<td>4.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Watch= Garmin GPS watch, Insole= Loadsol insole sensor, SPM= unilateral steps per minute

Participants in this study were asked to increase cadence by 10% and, on average, were able to achieve approximately 7% above their preferred. Yet, this change was sufficient to produce a decrease in peak impact force between cadence conditions. The results of this study support data reported by Heiderscheit, et al., where both 5% and 10% increases in cadence decreased energy absorption required at the knee by approximately 20% and 40%, respectively, as well as decreased energy absorbed at the hip (by ~57%) with 10% increase in cadence. Other studies suggest comparable benefits at the patellofemoral joint, with an average of 14% lower contact forces, and at the foot, with a decrease in overall plantar loading between 2.4–8.0%. Similarly, Willy, et al. described changes in multiple lower extremity loading variables at just 7.5% increase in cadence. These changes included a decrease in average vertical loading rate by 17.9% as well as instantaneous vertical loading rate by 18.9%. In contrast, Hobara, et al. reported a minimum of 15% increase in cadence to produce changes in lower extremity loading variables such as vertical loading rate and vertical impact peak. However, some have suggested increases above 10% may not be necessary to produce the desired lower extremity benefits and may negatively increase perceived exertion and metabolic cost during running.6,30

The results demonstrated in the current study may have implications for using cadence modifications to reduce peak impact force as well as promote the suggested benefits on other lower extremity loading variables during an outdoor run. Previous studies had suggested high impact forces are associated with development of common RRs, such as me-
dial tibial stress syndrome,\textsuperscript{32,33} Achilles tendinopathy,\textsuperscript{35,34} plantar fasciitis,\textsuperscript{35,35} and patellofemoral pain syndrome.\textsuperscript{33,36} However, a prospective study by Szymanek, et al.\textsuperscript{37} discovered no association between a runner’s preferred cadence and development of lower extremity overuse injuries. Additionally, a recent meta-analysis by Vannatta, et al.\textsuperscript{38} reported a conflicting association between peak impact force and RRI. In the same study, they reported limited evidence relating decreased step rate to increased risk of shin-related injuries.\textsuperscript{38} Further investigation into the use of cadence modification for the treatment or prevention of pain and RRI appears to be warranted as was suggested in their review.

Altering patient cadence with the goal of reducing impact forces may be feasibly accomplished in a clinical setting using a treadmill.\textsuperscript{5–8} The results of the present study demonstrate that similar cadence modifications can be feasibly implemented within an outdoor setting with the use of wearable technology and metronome feedback. Cadence measured through the GPS watch device was similar to the insole-measured cadence, indicating this commercially available technology may provide an effective method for measuring running cadence during outdoor gait retraining. This may open opportunities to provide running with cadence training protocols to be used in an outdoor running environment. This may also be a beneficial adjunct to training for military personnel where it has been reported that 25\% of male and 50\% of female military recruits suffer an injury related to their training, with 60–80\% of those injuries being considered an overuse lower extremity injury.\textsuperscript{39} Since much of military training is completed in an outdoor setting, use of a metronome and GPS watch may provide a feasible alternative for in-field feedback and cueing of cadence.

LIMITATIONS

This study had several limitations that may affect the interpretation of the findings presented here. First, the study was performed on only healthy runners who did not have a history of lower extremity injuries. Therefore, these results should not be considered to be representative of an injured running population. Further studies should examine if injured runners behave in a similar manner for cadence training in an outdoor setting. Second, although every attempt was made to control many of the elements in our outdoor setting, certain environmental variables were subject to change between baseline and cadence session procedures such as wind speed, temperature, and amount of vehicle traffic. These variables, even when minimized, may have an effect on the within-subject changes that were reported here. Third, the study consisted of an intervention performed with a small sample size of only 15 participants which may limit the power of statistical inferences. Further studies should include a greater number of participants to replicate these findings. Finally, while not a direct aim of this study, there was no long-term assessment of cadence retention without GPS watch and metronome use. Therefore, it is unknown whether these acute changes in cadence shown here through use of a metronome would be retained. However, Willy, et al.\textsuperscript{30} suggested maintenance of increased step frequency may be effective for a 30-day duration. Despite this, future research should examine for retention of cadence modifications over an extended period, as well as the potential for use of a fading feedback schedule, to promote long-term changes without reliance on concurrent feedback.

CONCLUSION

Using a metronome to increase cadence in an outdoor setting may be an effective way to reduce impact forces during running in an outdoor setting. Furthermore, using wearable technology that can provide cadence feedback via auditory cues may produce changes to cadence outside of the lab. Participants were immediately able to make a 7\% average increase in cadence within one session using a metronome, suggesting that this may be an effective tool for manipulating cadence during outdoor running. While further research is indicated to examine the cadence effects on RRI incidence and for "in the field" training, these findings demonstrate a possibility for cadence alterations to be feasible in outdoor settings.

CONFLICTS OF INTEREST

All authors report no conflict of interest associated with this project.

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REFERENCES


Does Daily Physical Activity Differ Between Patients with Femoroacetabular Impingement Syndrome and Patients with Hip Dysplasia? A Cross-Sectional Study in 157 Patients and 60 Healthy Volunteers

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Keywords: femoroacetabular impingement syndrome, hip dysplasia, accelerometry, physical activity

Background

The clinical presentation of femoroacetabular impingement syndrome (FAIS) and acetabular hip dysplasia (HD) are similar. However, the groups seem to differ regarding physical activity (PA) and sport.

Purpose

The aim was to compare PA between three groups; patients with FAIS, patients with HD, and healthy volunteers. A secondary purpose was to compare self-reported function in sport and recreation (sport/recreation) between patients with FAIS and HD.

Study Design

This study is a cross-sectional study on 157 patients with FAIS or HD and 60 healthy controls.

Methods

PA was measured with accelerometer-based sensors, and sport/recreation was measured with the Copenhagen Hip and Groin Outcome Score (HAGOS). Data on patients with FAIS or HD and healthy volunteers were collected in other studies and merged for comparison in this study.

Results

Fifty-five patients with FAIS (20 males; mean age 36 years), 97 patients with HD (15 males; mean age 30 years) and 60 healthy volunteers (24 males; mean age 31 years) were included. Compared with patients with HD, patients with FAIS spent more time on very low intensity PA (mean 73 minutes (95% CI: 45;102)) and less time on low intensity PA per day (mean -21 minutes (95% CI: -37;-6)). Both groups spent less time on high intensity PA per day compared with healthy volunteers (p≤0.03). However, sport/recreation did not differ between the two groups (FAIS: median 34 points (IQR: 22;50) and HD: median 38 points (IQR: 25;53), p=0.16).

Conclusion

Patients with FAIS appear to be less physical active compared with patients with HD.
However, both groups seem to perform less high intensity PA compared with healthy volunteers. This is interesting, as self-reported function in sport/recreation does not differ between patients with FAIS and HD. Thus, high intensity PA seems to be a key outcome in the management of patients with FAIS and HD.

**Level of Evidence**

**Level 2b**

**INTRODUCTION**

Femoroacetabular impingement syndrome (FAIS) and acetabular hip dysplasia (HD) are two of the most common hip diseases in young and middle-aged adults\(^1\) and diagnosed radiographically by acetabular and femoral angles and clinical symptoms of hip pain.\(^2\) Patients with FAIS either have pincer morphology, which is an over-coverage of the femoral head,\(^3\) cam morphology, consisting of a bump at the neck-head junction of the proximal femur,\(^4\) or a combination of the two. HD is typically described as a shallow and steep acetabulum with insufficient coverage of the femoral head.\(^5\) The literature describes patients with FAIS as athletic males,\(^6,7\) and focus in research has thus been on return to sport.\(^8\) In contrast, patients with HD are primarily females\(^2\) and only few studies have investigated their athletic status and return to sport.\(^9\) Thus, the clinical perception of the two groups seems to differ regarding physical activity (PA) and sport.

According to World Health Organization (WHO), PA includes the following four dimensions: Frequency, Intensity, Time and Type (F.I.T.T.).\(^10\) To obtain information on these dimensions of PA in daily living, accelerometer-based measurements by small, wearable sensors is considered ideal.\(^11,12\) Accelerometer-based PA have previously been investigated before and after hip preservation surgery in two cohorts of patient with FAIS or HD.\(^13,14\) Neither of the two cohorts changed accelerometer-based PA from before to one year after surgery.\(^15,14\) To the best of the authors’ knowledge, no previous studies have compared accelerometer-based PA between patients with FAIS and HD.

The aim of this study was to compare accelerometer-based PA, including the four dimensions of F.I.T.T., between three groups: patients with FAIS, patients with HD, and healthy volunteers. A secondary purpose was, to compare self-reported function in sport and recreation (sport/recreation) between patients with FAIS and HD.

**METHODS**

This cross-sectional study combined data from two previously published studies on patients with FAIS (HAFAI cohort study)\(^13\) and HD,\(^14\) and healthy volunteers from the ongoing PreserveHip trial.\(^15\) Data from healthy volunteers from the HAFAI cohort study and the PreserveHip trial were combined. Ethical approval from the Central Denmark Region Committee on Health Research Ethics and the Danish Data Protection Agency was obtained for each study and has been reported in the above mentioned studies.\(^13–15\)

**PATIENTS**

Patients with FAIS were included from the Department of Orthopedics at Horsens Hospital. The patients were diagnosed with FAIS according to the Warwick agreement\(^16\) and scheduled for hip arthroscopy. Further details on inclusion and exclusion criteria have been described previously.\(^17\)

Patients with HD were included from the Department of Orthopedics at Aarhus University Hospital. The patients were diagnosed with HD (Wiberg Center-Edge angle <25° and groin pain for at least three months) and scheduled for periacetabular osteotomy. Exclusion criteria have been described elsewhere.\(^18\)

In the HAFAI cohort study and the PreserveHip trial, the healthy volunteers were recruited by advertisements at Horsens Hospital, Aarhus University, Aarhus University Hospital, VIA University College and social media. Healthy volunteers were not considered eligible if they had experienced hip-related pain or problems within the prior year, had a history of previous major surgery on the hip, knee, ankle, back or if they had a neurological or rheumatoid disease affecting their hip function. In addition, healthy volunteers from the PreserveHip trial had a maximum Body Mass Index (BMI) of 25 since patients with a BMI above 25 were not candidates for periacetabular osteotomy. This was not the case for the healthy volunteers from the HAFAI cohort study, where BMI above 25 was not a part of the exclusion criteria.

**DATA COLLECTION**

Information on the participants’ daily PA was obtained with tri-axial accelerometer. Accelerometers of the model AX3 from Axivity Ltd. (Newcastle, UK) were used for patients with FAIS and healthy volunteers, while accelerometers of the model X16-mini from Gulf Coast Data Concepts (Waveland, MS, USA) were used for patients with HD. The accelerometers measured accelerations in three dimensions at 100 Hz for the AX3 model and 50 Hz for the X16-mini model. The accelerometers were worn on the lower extremity not scheduled for surgery and on the right leg for the healthy volunteers. The accelerometers were positioned at the lateral side of the thigh, halfway between the major trochanter and the lateral femoral condyle. Patients with FAIS and healthy volunteers from the HAFAI cohort study wore the accelerometer for five consecutive days. Patients with HD and healthy volunteers from the PreserveHip trial wore the accelerometer for seven consecutive days. All participants were asked to remove the accelerometer when sleeping and during swimming activities. The accelerometer used for the patients with HD was an older version that had to be removed before showering and recharged during nights. The participants were asked to make notes if and for
how long the accelerometer had been removed during the day. Accelerometers were returned to the hospitals afterwards.

DATA ANALYSIS

When the accelerometer and the participants’ notes were returned, data were downloaded using OMGUI Configuration and Analysis Tool (Version 1.0.0.45, Newcastle, UK). Data were then divided into days using a MatLab (MathWorks, Natick, USA) script developed at Aarhus University Hospital. After separating the datafile into days, data were analyzed using a validated algorithm.\textsuperscript{19} In short, each day was manually calibrated by selecting a period of walking, which enabled the algorithm to precisely identify different types of activities, such as number of steps, cadence of the stepping activity and the time spent walking, based on the average magnitudes of the three acceleration vectors and the gait cycle frequency.\textsuperscript{19} Based on this information, the algorithm also constructed an intensity parameter where each 10-second data window was grouped into one of the following four categories; (i) very low intensity PA e.g. sitting or standing (0-0.05 g), (ii) low intensity PA (0.05-0.1 g) e.g. standing or shuffling, (iii) moderate intensity PA (0.1-0.2 g) e.g. slow or normal walking and (iv) high intensity PA (>0.2 g) e.g. fast walking, running or jumping.\textsuperscript{19} Further details has been described by Liperts et al.\textsuperscript{19}

SELF-REPORTED FUNCTION IN SPORT/RECREATION

Self-reported hip function was obtained from The Copenhagen Hip and Groin Outcome Score (HAGOS).\textsuperscript{20} The subscale sport/recreation was the primary interest of this study, due to the possible difference in athletic status between the two disease groups. The questionnaire consists of five additional subscales: pain, symptoms, physical function in daily living, participation in physical activities and hip- and/or groin-related quality of life. Each subscale is converted into a score from 0-100, where a score of 100 indicates absence of hip-related problems. The HAGOS has been found to be reliable, valid, and responsive.\textsuperscript{20,21} The Minimal Important Change (MIC) of the subscale sport/recreation was 11 points in a cohort of Swedish patients with FAIS scheduled for hip arthroscopy.\textsuperscript{22}

STATISTICAL CONSIDERATIONS

Each day was analyzed separately and days containing less than eight hours were excluded. Moreover, since wear time varied between each participant, time spent on each physical activity parameter was normalized to total wear time at the individual level. Before initiating the statistical analyses, all continuous data were assessed for normality using histograms and probability plots. Normally distributed data were presented as means with standard deviations (SD) while non-normally distributed data were presented as medians with interquartile range (IQR), i.e. 25-75th percentile. Categorical data were presented as number of events with percentages of total events. The student t-test and the chi-square test was used to investigate if the groups differed regarding baseline characteristics. Differences between patients with FAIS and patients with HD on the different parameters of F.I.T.T. were investigated using multiple linear regression analyses. These analyses were adjusted for sex for two reasons. Firstly, the proportion of males within the two diseases differs significantly,\textsuperscript{2} and secondly, males were expected to perform more high impact PA than females. The Mann–Whitney U test was used to compare the non-normally distributed HAGOS subscales scores between patients with FAIS and patients with HD. Statistical analyses were performed using STATA 16.1 (StataCorp, College Station, TX, USA). This study was based on participants from other prospective studies. Thus, no sample size calculation was performed as the numbers of participants were fixed when planning this study.

RESULTS

Sixty patients with FAIS, 100 patients with HD and 66 healthy volunteers were included in this study (Figure 1). Fourteen patients could not be included in the analyses due to missing data. Three days among two patients with FAIS and ten days among eight healthy volunteers were excluded as these days contained less than eight hours of data. None of the patients with HD had worn the accelerometer for less than eight hours. Characteristics of participants revealed that there were fewer males among the patients with HD compared with patients with FAIS. In addition, patients with FAIS were older and had higher BMI compared with patients with HD (Table 1). Accelerometer-based PA for the three groups, described by the dimensions of F.I.T.T. is presented in Table 2.

DIFFERENCES IN ACCELEROMETER-BASED PA BETWEEN PATIENTS WITH FAIS, HD AND HEALTHY VOLUNTEERS

Compared with patients with HD, patients with FAIS spent more time on very low intensity PA and less time on low intensity PA (Table 3). However, patients with FAIS had worn the accelerometer for more time than patients with HD. Compared with healthy volunteers, patients with FAIS and HD spent less time on high intensity PA, running and cycling, and were more sedentary. However, patients with FAIS spent more time on very low intensity PA compared with healthy volunteers. Adjusting for sex did not change any of the results considerably. Noteworthy, two patients (one with FAIS and one with HD) had a considerably different PA level. Therefore, data from these patients were considered outliers. Accordingly, a sensitivity analyses were done without data on these patients, showing no changes of the results.

DIFFERENCES IN SELF-REPORTED SPORT/RECREATION BETWEEN PATIENTS WITH FAIS AND HD

Self-reported sport/recreation did not differ between patients with FAIS and patients with HD, and there were no differences in the other subscales of HAGOS between patients with FAIS and HD. Compared to the healthy volunteers, the patients reported about half the score of the healthy volunteers or lower, indicating that the patients are severely impaired by their hip disease.
Table 1. Characteristics of patients and healthy volunteers with accelerometer-based data.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>FAIS (n=55)</th>
<th>HD (n=97)</th>
<th>p-value (FAIS vs. HD)</th>
<th>Healthy volunteers (n=60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, no. males (%)</td>
<td>20 (36)</td>
<td>15 (15)</td>
<td>0.003</td>
<td>24 (40)</td>
</tr>
<tr>
<td>Mean age, years (SD)</td>
<td>36 (9)a</td>
<td>30 (9)</td>
<td>&lt;0.001</td>
<td>31 (9)</td>
</tr>
<tr>
<td>Mean weight, kg (SD)</td>
<td>76.5 (15.3)a</td>
<td>67.8 (11.1)</td>
<td>&lt;0.001</td>
<td>66.9 (9.6)</td>
</tr>
<tr>
<td>Mean height, m (SD)</td>
<td>1.73 (0.1)</td>
<td>1.71 (0.1)</td>
<td>0.06</td>
<td>1.73 (0.1)</td>
</tr>
<tr>
<td>Mean BMI, kg/m² (SD)</td>
<td>31 (5)a</td>
<td>23 (3)a</td>
<td>&lt;0.001</td>
<td>27 (2)</td>
</tr>
<tr>
<td>HAGOS, median (IQR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pain</td>
<td>53 (40-68)a</td>
<td>53 (38-65)a</td>
<td>0.74</td>
<td>100 (100-100)</td>
</tr>
<tr>
<td>Symptoms</td>
<td>46 (32-61)a</td>
<td>50 (36-61)a</td>
<td>0.38</td>
<td>100 (96-100)</td>
</tr>
<tr>
<td>Physical function in daily living</td>
<td>50 (35-70)a</td>
<td>55 (40-75)a</td>
<td>0.54</td>
<td>100 (100-100)</td>
</tr>
<tr>
<td>Physical function in sport/recreation</td>
<td>34 (22-50)a</td>
<td>38 (25-53)a</td>
<td>0.16</td>
<td>100 (100-100)</td>
</tr>
<tr>
<td>Participation in physical activities</td>
<td>13 (0-38)a</td>
<td>13 (0-38)a</td>
<td>0.67</td>
<td>100 (100-100)</td>
</tr>
<tr>
<td>Quality of life</td>
<td>30 (25-40)a</td>
<td>30 (20-35)a</td>
<td>0.40</td>
<td>100 (110-100)</td>
</tr>
</tbody>
</table>

FAIS = Femoroacetabular impingement syndrome. HD = hip dysplasia. SD=Standard Deviation. IQR=Interquartile range (25-75th percentile). *Statistically significant different compared with healthy volunteers.

Figure 1. Flow chart of patients and healthy volunteers.

DISCUSSION

Accelerometer-based PA, described by the four dimensions of F.I.T.T. differed between patients with FAIS and HD regarding time spent on very low and low intensity PA. Compared with patients with HD, patients with FAIS spent 73 minutes more time per day on very low intensity PA and 21 minutes less time per day on low intensity PA. The difference in accelerometer wear time between the two groups may explain the difference in time spent on very low intensity PA. Patients with FAIS wore the accelerometer for an average of 47 minutes longer per day compared with patients with HD. Since both groups were instructed to wear the accelerometer during all waking hours, late evening wear time could be characterized by sedentary PA, possibly explaining the difference in time spent on very low intensity PA. This is further supported by the findings of no differences in number of steps, cadence, time on high intensity PA, number of sit to stand transfers and time spent on walking, standing and cycling between patients with FAIS and HD. In addition, there were no differences between the two groups in any of the HAGOS subscales.

Compared with the healthy volunteers, patients with FAIS spent less time on low and high intensity PA. In contrast to the results of this study, Kierkegaard et al. did not find a difference in time spent on different intensity PA's between patients with FAIS and HD. In addition, there were no differences between the two groups in any of the HAGOS subscales.

Compared with the healthy volunteers, patients with FAIS spent less time on low and high intensity PA. In contrast to the results of this study, Kierkegaard et al. did not find a difference in time spent on different intensity PA's between patients with FAIS and healthy volunteers. This indicates that the difference found in this study could be related to the sampling of healthy volunteers collected in the PreserveHip trial or that the bigger sample improves chances of finding a statistically significant difference. Patients with HD differed from the healthy volunteers on time spent on high intensity PA, with a 14 minutes difference per day. Compared with the healthy volunteers, patients with
Table 2. Physical activity per day in patients with FAIS, patients with HD and healthy volunteers described by the dimensions of F.I.T.T.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Parameter</th>
<th>FAIS (n=55)</th>
<th>HD (n=97)</th>
<th>Healthy volunteers (n=60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Steps total, no.</td>
<td>8038 (3348)</td>
<td>7696 (2849)</td>
<td>7904 (2534)</td>
</tr>
<tr>
<td>Intensity</td>
<td>Cadence, steps/min</td>
<td>97.3 (7.3)</td>
<td>98.3 (6.7)</td>
<td>98.9 (7.0)</td>
</tr>
<tr>
<td></td>
<td>Very low intensity PA, min</td>
<td>713 (82)</td>
<td>639 (85)</td>
<td>622 (118)</td>
</tr>
<tr>
<td></td>
<td>Low intensity PA, min</td>
<td>100 (43)</td>
<td>121 (47)</td>
<td>116 (43)</td>
</tr>
<tr>
<td></td>
<td>Moderate intensity PA, min</td>
<td>52 (24)</td>
<td>57 (25)</td>
<td>60 (22)</td>
</tr>
<tr>
<td></td>
<td>High intensity PA, min</td>
<td>40 (25)</td>
<td>38 (18)</td>
<td>50 (22)</td>
</tr>
<tr>
<td>Time</td>
<td>Wear time, min</td>
<td>904 (91)</td>
<td>855 (69)</td>
<td>847 (103)</td>
</tr>
<tr>
<td></td>
<td>Walking, min</td>
<td>101 (39)</td>
<td>99 (37)</td>
<td>97 (29)</td>
</tr>
<tr>
<td></td>
<td>Standing, min</td>
<td>254 (83)</td>
<td>220 (84)</td>
<td>246 (74)</td>
</tr>
<tr>
<td></td>
<td>Sedentary, min</td>
<td>541 (107)</td>
<td>529 (104)</td>
<td>485 (95)</td>
</tr>
<tr>
<td></td>
<td>Running, min</td>
<td>1 (2)</td>
<td>1 (3)</td>
<td>4 (7)</td>
</tr>
<tr>
<td></td>
<td>Cycling, min</td>
<td>7 (12)</td>
<td>6 (9)</td>
<td>15 (12)</td>
</tr>
<tr>
<td>Type</td>
<td>Sit to stand transfers, no.</td>
<td>55 (18)</td>
<td>55 (21)</td>
<td>55 (13)</td>
</tr>
</tbody>
</table>

Results are presented as mean with standard deviations (SD). Abbreviations: FAIS=Femoroacetabular impingement syndrome; HD=hip dysplasia; F.I.T.T.=frequency, intensity, time and type; no.=number, min=minutes; PA=physical activity.

FAIS and HD spent more time per day being sedentary, revealing a more inactive lifestyle, possibly a consequence of the hip disease or sequelae related to the hip disease. In addition, patients also differed form healthy volunteers regarding time spent on high intensity PA (e.g. fast walking, running or jumping, etc.), indicating that the longstanding hip disease or sequelae related to the hip disease possibly prevented the patients from performing these activities. Therefore, high intensity PA seems to be a key outcome when managing patients with FAIS and HD.

Health professionals are advised to highlight the benefits of meeting PA recommendations (i.e. 150 minutes of moderate intensity aerobic PA or 75 minutes of high intensity aerobic PA per week). In this study, patients with FAIS performed 52 minutes of moderate intensity PA per day and 40 minutes of high intensity PA per day. Patients with HD performed 57 minutes of moderate intensity PA per day and 38 minutes of high intensity PA per day. The healthy volunteers performed 60 minutes of moderate intensity PA per day and 50 minutes of high intensity PA per day. Hence, the two patient groups and the healthy volunteers met the weekly recommendations regarding daily PA. Patients as well as the healthy volunteers had a mean of daily steps close to 8000, with a cadence close to 100. This is in accordance with the minimum recommendations for physical activity reported by Tudor-Locke et al., who estimated the minimum amount of daily steps to be 7000-8000 for healthy adults, with a cadence on 100 steps per minute.25

Harris-Hayes et al. investigated the number of strides per day in 74 patients with FAIS and 24 patients with HD, using a step watch.24 They found that patients with FAIS had an average of 5095 daily strides (corresponding to 10,190 steps per day), while patients with HD had an average of 4627 daily strides (corresponding to 9254 steps per day).24 Accordingly, the number of daily steps found by Harris-Hayes et al. is higher than the average number of daily steps found in the current study, suggesting that the patients in our study could be more impaired by their underlying hip disease or had a lower daily PA level. In addition, Harris-Hayes et al. found that the number of daily strides for patients with FAIS and HD were similar to the number of daily strides for a group of 20 asymptomatic controls.24 The asymptomatic controls had an average of 5192 daily strides (corresponding to 10,384 steps per day), which was also considerably higher compared with the healthy volunteers in the current study.24 This indicates that the differences could be due to the two different methods used to measure steps and strides.

The current study has several strengths. Firstly, the usage of a validated algorithm, which ensures the validity of the estimates.19 Secondly, the accelerometer wear time covered both weekends and weekdays for at least eight hours a day. Thirdly, the adjustment of analyses, based on the assumption that sex could be a confounder for the association between hip problems and PA. However, the adjusted analysis revealed that sex was not a confounder for the association between hip disease and PA. The study, however, also has some limitations. Firstly, the usage of two different accelerometer-based sensors could negatively have impacted on the wear time of the sensor used by the patients, since the sensor worn by patients with HD had to be removed before showering as well as recharged during the night. In addition, the older sensor was sampling at a lower frequency than the newer model. The different sensors could have explained some of the difference regarding wear time between the two patient groups. However, wear time was not different between patients with HD and healthy volunteers, although PA of the volunteers was measured with
Table 3. Mean differences in physical activity per day between patients with FAIS and HD described by the dimensions of F.I.T.T.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Parameter</th>
<th>Unadjusted mean (95% CI)</th>
<th>p-value</th>
<th>Adjusted° mean (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Steps total, no.</td>
<td>342 (-671;1355)</td>
<td>0.51</td>
<td>445 (-600;1489)</td>
<td>0.40</td>
</tr>
<tr>
<td>Intensity</td>
<td>Cadence, steps/min</td>
<td>-1.0 (-3.3;1.3)</td>
<td>0.40</td>
<td>-0.5 (-2.9;1.9)</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Very-low intensity PA, min</td>
<td>74 (46;102)</td>
<td>&lt;0.001</td>
<td>73 (45;102)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Low intensity PA, min</td>
<td>-21 (-36;-6)</td>
<td>0.01</td>
<td>-21 (-37;-6)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Moderate intensity PA, min</td>
<td>-5 (-14;3)</td>
<td>0.19</td>
<td>-7 (-15;2)</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>High intensity PA, min</td>
<td>2 (-5;9)</td>
<td>0.51</td>
<td>2 (-5;9)</td>
<td>0.65</td>
</tr>
<tr>
<td>Time</td>
<td>Wear time, min</td>
<td>50 (24;76)</td>
<td>&lt;0.001</td>
<td>47 (20;74)</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Walking, min</td>
<td>2 (-11;14)</td>
<td>0.76</td>
<td>2 (-11;15)</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Standing, min</td>
<td>34 (6;62)</td>
<td>0.02</td>
<td>36 (8;65)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Sedentary, min</td>
<td>12(-23;47)</td>
<td>0.49</td>
<td>7 (-29;43)</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Running, min</td>
<td>0.06 (-0.87;0.98)</td>
<td>0.90</td>
<td>-0.02 (-0.98;0.93)</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Cycling, min</td>
<td>2 (-2;5)</td>
<td>0.39</td>
<td>1 (-2;5)</td>
<td>0.46</td>
</tr>
<tr>
<td>Type</td>
<td>Sit to stand transfers, no.</td>
<td>0.1 (-6.5;6.7)</td>
<td>0.98</td>
<td>1.2 (-5.6;8.0)</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Mean differences between FAIS and HD°

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Parameter</th>
<th>Unadjusted mean (95% CI)</th>
<th>p-value</th>
<th>Adjusted° mean (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Steps total, no.</td>
<td>134 (-957;1225)</td>
<td>0.81</td>
<td>79 (-983;1141)</td>
<td>0.88</td>
</tr>
<tr>
<td>Intensity</td>
<td>Cadence, steps/min</td>
<td>-1.6 (-4.3;1.0)</td>
<td>0.22</td>
<td>-1.7 (-4.3;1.0)</td>
<td>0.22</td>
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<tr>
<td></td>
<td>Very low intensity PA, min</td>
<td>91 (53;128)</td>
<td>&lt;0.001</td>
<td>92 (55;129)</td>
<td>&lt;0.001</td>
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<tr>
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<td>Low intensity PA, min</td>
<td>-16 (-32;0.03)</td>
<td>0.05</td>
<td>-16 (-32;-0.4)</td>
<td>0.05</td>
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<td>Moderate intensity PA, min</td>
<td>-8 (-16;0.6)</td>
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<td>-8 (-17;0.4)</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>High intensity PA, min</td>
<td>-9 (-18;-1)</td>
<td>0.03</td>
<td>-10 (-18;-1)</td>
<td>0.02</td>
</tr>
<tr>
<td>Time</td>
<td>Wear time, min</td>
<td>57 (21;93)</td>
<td>0.002</td>
<td>58 (22;94)</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>Walking, min</td>
<td>41 (9;17)</td>
<td>0.54</td>
<td>4 (-9;16)</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Standing, min</td>
<td>8 (-21;38)</td>
<td>0.57</td>
<td>9 (-20;38)</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Sedentary, min</td>
<td>56 (18;93)</td>
<td>0.004</td>
<td>56 (19;94)</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>Running, min</td>
<td>-3 (-5;1)</td>
<td>0.003</td>
<td>-3 (-5;1)</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>Cycling, min</td>
<td>-8 (-12;3)</td>
<td>0.001</td>
<td>-8 (-12;3)</td>
<td>0.001</td>
</tr>
<tr>
<td>Type</td>
<td>Sit to stand transfers, no.</td>
<td>-0.1 (-5.8;5.6)</td>
<td>0.98</td>
<td>0.01 (-5.7;5.7)</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Mean differences between FAIS and healthy volunteers°

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Parameter</th>
<th>Unadjusted mean (95% CI)</th>
<th>p-value</th>
<th>Adjusted° mean (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Steps total, no.</td>
<td>-208 (-1095;679)</td>
<td>0.64</td>
<td>-558 (-1461;346)</td>
<td>0.23</td>
</tr>
<tr>
<td>Intensity</td>
<td>Cadence, steps/min</td>
<td>-0.7 (-2.9;1.6)</td>
<td>0.56</td>
<td>-1.2 (-3.5;1.1)</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Very low intensity PA, min</td>
<td>17 (-15;49)</td>
<td>0.30</td>
<td>26 (-6;59)</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Low intensity PA, min</td>
<td>5 (-10;20)</td>
<td>0.51</td>
<td>2 (-13;17)</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Moderate intensity PA, min</td>
<td>-3 (-10;5)</td>
<td>0.53</td>
<td>-4 (-13;4)</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>High intensity PA, min</td>
<td>-12 (-18;-5)</td>
<td>&lt;0.001</td>
<td>-14 (-21;-8)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time</td>
<td>Wear time, min</td>
<td>7 (-20;35)</td>
<td>0.59</td>
<td>10 (-18;38)</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Walking, min</td>
<td>2 (-9;13)</td>
<td>0.73</td>
<td>-2 (-13;10)</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Standing, min</td>
<td>-26 (-52;0.3)</td>
<td>0.05</td>
<td>-21 (-48;6)</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Sedentary, min</td>
<td>44 (11;76)</td>
<td>0.01</td>
<td>45 (11;79)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Running, min</td>
<td>-3 (-5;1)</td>
<td>&lt;0.001</td>
<td>-3 (-4;1)</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Mean differences between HD and healthy volunteers°

International Journal of Sports Physical Therapy
the newer accelerometer. In addition, time spent on different activities was normalized to total wear time at the individual level. Therefore, the usage of two different accelerometer models does not seem to have influenced our results. Secondly, the daily PA level of the healthy volunteers may be overestimated due to some degree of volunteer bias as participation is probably associated with health consciousness and an active lifestyle. In addition, the healthy volunteers had to meet the predefined inclusion criteria which may have resulted in being healthier and more active than the average Danish citizen. However, a great effort was done to minimize healthy volunteer bias by including volunteers from many different institutions as well as the patient’s own network. Thirdly, several comparisons were made which by chance will increase the chance of finding a false significant result. However, all comparisons were formulated prior to the statistical analyses. Therefore, multiple comparison bias is not considered problematic in this study.

CONCLUSION

Patients with FAIS appear to be less physically active compared with patients with HD. However, both groups seem to perform less high intensity PA compared with healthy volunteers. This is interesting, as self-reported function in sport/recreation does not differ between patients with FAIS and HD. Thus, high intensity PA seems to be a key outcome in the management of patients with FAIS and HD.

CONFLICT OF INTEREST

None.

ACKNOWLEDGEMENTS

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REFERENCES


Original Research

An Investigation of the Association between Transversus Abdominis Myofascial Structure and Activation with Age in Healthy Adults using Ultrasound Imaging

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1 University of Sherbrooke, 2 Spine & Joint Centre, 3 University of Padova, 4 University of Sherbrooke; Research Center on Aging CIUSSS de l’Estrie

Keywords: ultrasound, age, fascia, transversus abdominis, ultrasound imaging

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Background
Because of their importance in core stability, training the deep abdominal muscles, fascial structures and particularly the transversus abdominis, is a key component of many sport and physical therapy programs. However, there are gaps in knowledge about age-related changes in the structure and activation capacity of these muscles.

Hypothesis/Purpose
This study investigated the association between deep abdominal muscles and fascial structures and transversus abdominis activation with age in healthy adults.

Study design
A cross-sectional study.

Methods
Eighty-six adults aged 18 to 77 participated in this study. An ultrasound image of their transversus abdominis, internal oblique, external oblique and associated fasciae was first captured at rest, then during a contraction of the transversus abdominis. Bivariate correlation analyses and hierarchical analyses were performed (significance level: \( p < 0.05 \)).

Results
The thickness of these three muscles decreases with age (\( \rho = -0.66 \) for external oblique, -0.51 for internal oblique and -0.58 for transversus abdominis), whereas the thickness of their fasciae increases (\( \rho = 0.39 \) for the fascia of external oblique, 0.54 for the fascia between internal oblique and external oblique, and 0.74 for the fascia between internal oblique and transversus abdominis). Transversus abdominis activation decreases with age (\( r = -0.44 \)). Age accounts for 19.5% of the variance in transversus abdominis activation.

Conclusion
These results demonstrate that normal aging is associated with changes in deep abdominal myofascial structures and transversus abdominis activation. Assessment of these metrics can provide valuable baseline information for physical therapists involved in rehabilitation and strengthening programs targeting older individuals.
INTRODUCTION

The internal oblique (IO), external oblique (EO) and transversus abdominis (TrA) are deep abdominal muscles involved in many functions such as breathing, postural control and during performance of functional activities and sports. The TrA in particular has been the focus of many studies. This muscle works in synergy with the multifidus, the diaphragm and the pelvic floor muscles to ensure lumbo pelvic stabilization. The TrA also plays a key role in anticipatory postural control. This type of postural control is described as an involuntary TrA contraction, planned and coordinated by the central nervous system, prior to a movement of a limb to provide initial stability of the trunk during physical activities. Impairment in core muscles activation and postural adjustments has been observed in older adults, which could potentially contribute to the high prevalence of low back pain episodes in this population. Evidence suggests that alterations in core muscle recruitment and injury risk exists and that appropriate training may reduce injury. Therefore, alteration in TrA activation often serves as a rationale for sports rehabilitation exercise programs. Since most studies on TrA structure and function involve young participants, there are gaps in knowledge on age-related changes in deep abdominal muscle structure and TrA function. Increasing numbers of people aged 40+ are participating in Master sport activities, and this relationship needs to be investigated so that physical therapists know whether the changes they observe during an assessment are due to normal aging or a pathological condition.

Ultrasound (US) imaging is now commonly used by physical therapists to evaluate muscle structure and function, or as a biofeedback tool for rehabilitation of neuromuscular control. Abdominal muscle structure and activation can be assessed with this imaging technology. Structure measurements refer to morphometric parameters like thickness. Muscle activation can be quantified by differences in muscle thickness measured while the muscle is in a contracted and relaxed state. US imaging techniques have been reported to show higher reliability and validity in measuring thickness and muscle activation compared to more conventional methods such as magnetic resonance imaging or EMG. Two US studies on age-related changes in abdominal muscles concluded that the EO and IO muscles were thinner in older individuals compared to younger people. However, the differences in TrA thickness were small or not statistically significant. Since these studies were conducted in women only, there is insufficient evidence to conclude on age-related US imaging features of abdominal muscles. Furthermore, the association between abdominal muscle activation patterns and age is not yet clearly established. The few studies that have investigated this topic used EMG with conflicting results and did not specifically focus on TrA activation. Diminished abdominal muscle activation during various tasks was found in older adults by Hanada et al. and Caix et al., whereas Peach et al. demonstrated greater activation of these muscles during trunk movement. More research is needed to shed light on the association between age and TrA activation.

To comprehend their function, muscles and their associated connective tissue (their fascia), should not be regarded as isolated tissue, but as an integrated functional myofascial unit. As with any muscle in the body, the abdominal muscles are embedded in intramuscular connective tissue (the perimysium and endomysium) and are surrounded by a thin layer of dense connective tissue (the epimysial fascia). Epimysial fascia plays a key role in the transmission of muscle force during contraction. One key characteristic of age-related muscle decline is sarcopenia, progressive atrophy characterized by an increase in connective tissue and a decrease in muscle fiber volume. One possible avenue for a better understanding of impaired muscle activation with age is examining the changes in the connective tissue, which tends to dehydrate, to store additional collagen and to thicken. With this in mind, it seems logical to assume that age-related modifications of the TrA fascia combined with muscle atrophy could impair TrA activation. Therefore, important information about the association between TrA activation with age may be missed if the role of the fascia is not considered.

The primary objective of this study was to investigate the association between TrA myofascial structure and activation with age in a population of healthy adults aged 18 to 80. We hypothesized that a negative correlation with age would be observed with the TrA muscle component of the unit, but that the correlation would be positive with respect to the epimysial fascia component; we also postulated that a negative correlation with age would be observed with TrA activation. As a secondary objective, the association between IO and EO myofascial structures with age was investigated to provide a more complete portrait of the age-related changes of all the deep abdominal muscles.

METHODS

STUDY DESIGN

A cross-sectional study was conducted at the Research center of the CHUS, CIUSSS de l’Estrie, Sherbrooke, Canada. Data were collected between July 2018 and March 2020. This project was approved by the institutional review boards. All participants provided signed informed consent prior to participation.

PARTICIPANTS

Eighty-six participants (men and women) between 18 and 77 years of age were recruited via convenience sampling from the recruitment bank of the Research Center on Aging, CIUSSS de l’Estrie – CHUS, Sherbrooke, Canada and from posters displayed around campus. In this study, normal aging was characterized as the absence of acute or chronic disabling diseases; the ability to meet one’s health, housing, food, and leisure needs; and the possibility of leading an
active and satisfying life. Based on these elements and inspired by the Baltimore Longitudinal Study of Aging,28 the inclusion criteria were: 1) aged between 18 and 80 years, 2) good general health (no chronic condition limiting activities or requiring punctual care), 3) independent community dwellers (had no difficulties in performing self-care or activities of daily living), 4) able to walk independently for short distances (at least 400 meters) without experiencing any shortness of breath. Exclusion criteria were: 1) a body mass index greater than 30 kg/m²; 2) an elite or active competitive athlete; 3) a history of spinal, abdominal, thoracic, or lower extremity surgery in the past two years; 4) known neurological disorder, respiratory condition (e.g.: chronic obstructive pulmonary disease) or structural scoliosis; 5) previous TrA-specific training experience; 6) back pain in the previous 12 months or pain elsewhere in the previous 7 days.29 A sample size of 85 participants was needed, considering an expected correlation coefficient of 0.3 (Cohen’s medium effect size30), a power of 80% and an alpha of 0.05.

EXPERIMENTAL PROCEDURE

Upon their arrival at the laboratory, participants completed a questionnaire that included questions about their age and general health. Height and weight measurements were taken and an US examination was performed. All participants were assessed in a standardized supine position with knees flexed at 90°. Ultrasound measurements (GE Logic e, 13 MHz linear probe, B-mode) were performed by two physiotherapists trained in musculoskeletal US imaging, having used this technique in their daily rehabilitation practice for 3 and 5 years, respectively. The abdomen was exposed and US gel was used at the skin-probe interface to optimize acoustic transmission. The probe was positioned midway between the 12th rib and the iliac crest in the transverse axis, and then was moved laterally over the anterior axillary line until the rim of the thoracolumbar fascia was at the edge of the screen. This provided a clear image of the three abdominal wall muscles (EO, IO and TrA – see Fig. 1).10,29

The use of anatomical landmarks (as opposed to superficial skin landmarks) improved reliability and coincided with clinical practice.11 Three images were captured at rest at the end of expiration. Then, participants were taught about the anatomy of abdominal wall muscles and were instructed on how to engage their TrA using a validated, standardized hollowing (drawing-in) maneuver: "Breathe in, breathe out, and draw your navel in towards your spine."51 They were taught to ‘read’ the US image to monitor their performance throughout the training session. The education (5 min) and training (10 min) sessions lasted 15 minutes in total. All participants successfully activated their TrA within five trials or less, and a total of 10 repetitions was asked to consolidate their learning of the task.32 After a five-minute break, the US machine was positioned so that participants could not see the screen. They were then asked to engage their TrA again after the same standardized hollowing manoeuvre instructions were given. The contraction was held for two seconds; three TrA contractions were performed (with 60 sec rest between each contraction) and one image was captured per contraction. All images were captured on the left side and at the end of expiration to standardize the effect of breathing.11 All images were anonymized and stored on the US machine’s hard drive for analysis.

OUTCOME MEASURES

Myofascial structure of the TrA, IO, and EO: In this study, myofascial structure refers to the thickness of the muscles and their related epimysial fascia. All thickness measurements were carried out by a third physiotherapist blinded to the study with 7 years of experience in musculoskeletal US imaging. On US images, fasciae are seen as linear hyperechoic lines representing the fibrous connective tissue layers, adjacent to a hypoechoic band of muscular tissue.

Muscle thickness measurements were made at the thickest part of each muscle, in a direction perpendicular to the skin with the US machine’s built-in calipers and measurement software. The thickness of a given muscle corresponded to the distance between one caliper positioned on the superior border of hypoechoic muscle band and another caliper positioned on the inferior border. The thickness of all epimysial fasciae corresponded to the distance between one caliper positioned on the superior border of the hyperechoic lines and another caliper positioned on the inferior border. Thickness measurements were taken on the three images taken at rest, and the mean value was used for analysis. The intraclass correlation coefficients (ICC) for interrater reliability reported with this measurement technique are greater than or equal to 0.95.11

Thickness of the epimysial fascia was measured for the following structures: the anterior fascia of the EO muscle (superior relative to the US image) (FEO), the fascia between the EO and IO muscles (FEO/IO) and the fascia between the IO and TrA muscle (FIO/TrA). Thickness measurements of the posterior TrA fascia were not taken due to inconsistencies and poor resolution. The thickness of all epimysial fasciae corresponded to the distance between one
Table 1. Descriptive characteristics of the population sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>n (%)</th>
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<tbody>
<tr>
<td>Total sample</td>
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<table>
<thead>
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<th>Age range</th>
<th>n (%)</th>
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<td>18 – 39 years</td>
<td>31 (36%)</td>
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<tr>
<td>40 – 59 years</td>
<td>27 (31%)</td>
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<td>60 – 77 years</td>
<td>28 (33%)</td>
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<table>
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<tr>
<th>Women / men</th>
<th>n (%)</th>
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<tbody>
<tr>
<td>Women</td>
<td>52 (60%)</td>
</tr>
<tr>
<td>Men</td>
<td>34 (40%)</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Mean ± SD</th>
<th>Minimum</th>
<th>Maximum</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>45.16 ± 19.71</td>
<td>19.00</td>
<td>77.00</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65.9 ± 9.95</td>
<td>50.04</td>
<td>91.51</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.67 ± 0.09</td>
<td>1.52</td>
<td>1.90</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.69 ± 3.33</td>
<td>17.93</td>
<td>29.91</td>
</tr>
</tbody>
</table>

SD: standard deviation

SD: standard deviation

caliper positioned on the superior border of the hyperechoic lines and another caliper positioned on the inferior border (ICC = 0.85 for interrater reliability). Three thickness measurements were made for each epimysial fascia at equidistant intervals (0.4 cm) along a length of 1.2 cm (Figure 1). The mean of these three values was calculated for each of three images, and the mean fascia thickness of all three images was used for statistical analysis.

TrA activation: The standardized drawing-in maneuver requires the TrA to be active at low level of force. Hodges et al. showed that TrA activation measured with US imaging accurately reflect the intensity of contraction at relatively low levels (up to 20% of maximal voluntary contraction). In the present study, TrA activation was characterized by the Activation Ratio (AR). The TrA AR represents a participant’s ability to contract the TrA and is obtained by dividing the absolute TrA thickness (in mm) during contraction by the absolute TrA thickness at rest (see below).

\[
\text{TrA AR} = \frac{\text{TrA contracted}}{\text{TrA at rest}}
\]

STATISTICAL ANALYSIS

The Shapiro-Wilk test was performed to test the normality of the distribution. Mean, standard deviation (SD), minimum, maximum, and percentage values were used to describe the participants and outcome measures (muscles and fasciae structure and TrA activation). To complement the description of the metrics, Kruskal-Wallis and Steel-Dwass-Critchlow-Fligner tests were carried out to verify if there was a significant difference in thickness between the three muscles and between the three fasciae of interest. Mann-Whitney U tests were performed to compare muscle and fascia thickness between men and women. To achieve the primary objective of the study, bivariate correlation coefficients were used to investigate the association between myofascial structures and TrA activation with age. Because of the presence of normally distributed data for two variables (TrA AR and TrA muscle thickness) out of eight, we chose to calculate Pearson’s correlation coefficients (r) and Spearman’s rank (ρ) correlation coefficients and since the results confirmed no difference between parametric and nonparametric approaches, only nonparametric statistics are reported. The guide established by Akoglu et al. was used to interpret the strength of the correlations (<0.4=weak, 0.4–<0.7=moderate, 0.7–0.9=strong, >0.9=very strong). Finally, hierarchical regression analyses were conducted to explain the variance of TrA activation considering TrA muscle thickness, TrA epimysial fascia thickness (FIO/TrA) and age as explanatory variables. The level of significance for all analyses was set at \( p < 0.05 \).

RESULTS

PARTICIPANTS

A total of 86 participants (52 women and 34 men) were recruited; the participants’ characteristics are presented in Table 1.

DESCRIPTIVE STATISTICS FOR MYOFASCIAL STRUCTURE AND TRA ACTIVATION

Mean (±SD) values for the three muscles and fasciae structure and for TrA activation outcomes for all participants and for men and women are presented in Table 2. The results of the Mann-Whitney tests for the muscle and fascia thickness comparisons between sexes showed that men had significantly greater muscle thickness than women; however, no significant differences were found between sexes for fascia thickness and for TrA activation. The results of the thickness comparisons between the three muscles and between the three fasciae are shown in Figure 2 and Figure 3, respectively. For the muscle thickness comparisons, as shown in Figure 2, a significant pattern (\( p < 0.001 \)) of increasing order of median abdominal muscle thickness was found: TrA < EO < IO. A significant difference in fascia thickness was
Table 2. Descriptive statistics for myofascial structures and TrA activation

<table>
<thead>
<tr>
<th></th>
<th>Mean (±SD)</th>
<th>Mean (±SD)</th>
<th>Mean (±SD)</th>
<th>p values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>all participants</td>
<td>men</td>
<td>women</td>
<td>men vs women</td>
</tr>
<tr>
<td>Muscle thickness (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EO</td>
<td>4.44 (± 1.60)</td>
<td>4.93 (± 1.12)</td>
<td>3.69 (± 2.11)</td>
<td>p = 0.04*</td>
</tr>
<tr>
<td>IO</td>
<td>6.77 (± 1.94)</td>
<td>7.69 (± 2.22)</td>
<td>6.17 (± 1.49)</td>
<td>p = 0.002*</td>
</tr>
<tr>
<td>TrA</td>
<td>3.33 (± 0.81)</td>
<td>3.67 (± 0.95)</td>
<td>3.14 (± 0.65)</td>
<td>p = 0.012*</td>
</tr>
<tr>
<td>Fascia thickness (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEO</td>
<td>0.93 (± 0.27)</td>
<td>0.98 (± 0.32)</td>
<td>0.89 (± 0.24)</td>
<td>p = 0.27</td>
</tr>
<tr>
<td>FIO/EO</td>
<td>0.77 (± 0.29)</td>
<td>0.82 (± 0.29)</td>
<td>0.72 (± 0.28)</td>
<td>p = 0.16</td>
</tr>
<tr>
<td>FIO/TrA</td>
<td>0.79 (± 0.30)</td>
<td>0.82 (± 0.29)</td>
<td>0.78 (± 0.31)</td>
<td>p = 0.71</td>
</tr>
<tr>
<td>TrA activation (ratio)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TrA AR</td>
<td>1.53 (± 0.23)</td>
<td>1.60 (± 0.32)</td>
<td>1.48 (± 0.23)</td>
<td>p = 0.10</td>
</tr>
</tbody>
</table>

IR: interquartile range; EO: external oblique; IO: internal oblique; TrA: transversus abdominis; FEO: fascia superior to the external oblique; FIO/EO: fascia between internal oblique and external oblique; FIO/TrA: fascia between internal oblique and transversus abdominis; TrA AR: transversus abdominis activation ratio. * statistically significant difference, Mann-Whitney U test, p<0.05.

The Spearman’s rank correlation coefficients for myofascial structures and TrA activation with age as independent variables are presented in Table 3. Moderate, negative significant correlations were found for the muscle thickness of all three muscles (as dependent variables) and age (ρ = -0.66 for EO, -0.51 for IO and -0.59 for TrA), indicating that the thickness of these three muscles decreases with age. Moderate, positive significant correlations were found for the thickness of FEO and FIO/EO with age (ρ = 0.39 for FEO and 0.54 for FIO/EO), whereas a strong positive correlation was found for FIO/TrA (ρ = 0.74). These data demonstrate that fascia thickness increases as people age. With respect to correlations for TrA activation with age, a moderate, significant negative correlation was found for the activation ratio (TrA AR). In other words, TrA activation seems to decrease with advancing age.

Hierarchical regression analysis was used to explain TrA AR with age, gender, TrA muscle thickness and TrA fascia thickness (FIO/TrA). The results are presented in Table 4. The first model showed that age accounts for 19.5% of the variance of TrA AR (F1,84 = 20.295, R² = 0.195; p = 0.000). Adding sex to the model added 3.6% to the prediction of TrA AR (F1,83 = 3.848, R² = 0.056; p = 0.05). However, adding TrA thickness did not account significantly to the variance in TrA AR (F1,82 = 0.178, R² = 0.002; p = 0.674), nor did the addition of FIO/TrA (F1,81 = 1.520, R² = 0.014; p = 0.221).

DISCUSSION

This study is the first to investigate abdominal muscular structure considering epimysial fasciae and TrA activation...
Abdominal fascial thickness values are reported in three other studies.\textsuperscript{12,33,39} The thickness values reported in the present study are very similar to those reported in the reliability study published by Pirri et al.\textsuperscript{33} However, their thickness measurements were based only on one participant. It would have been interesting to know whether the similarity would have continued if the data had been collected on a larger sample. The current results cannot be compared to the other two studies\textsuperscript{12,39} due to differences in methods. Neither study reported individual epimysial fascia thicknesses, but both reported the sum of all fascia thickness measurements. Even if we calculate the sum of all 3 fascia measurements, none of the 3 studies considered the same fasciae in the equation. As for Whittaker et al.,\textsuperscript{12} gender effect was not present for fascia thickness.

The results related to the primary objective of the study demonstrate that a negative correlation was found between muscle thickness and age, while a positive correlation was observed between the epimysial fasciae associated with these muscles and age. A negative correlation was also found between TrA activation and age. These results are in accordance with the authors’ hypotheses. If we look more closely at the association of muscle thickness with age, a significant reduction in muscle thickness for all muscles investigated (EO, IO, and TrA) was observed with age. A negative association between all three muscles thicknesses and age was also observed by Rankin et al.\textsuperscript{36} in a population similar to that of the present study. Tahan et al\textsuperscript{10} and Ota et al\textsuperscript{19} also observed a negative association between EO and IO, but not TrA. This discrepancy with the TrA can be related to the participants’ characteristics. The population sample for the study by Ota et al. only included women. Studies have shown that a decline in muscle mass with age is more evident in men,\textsuperscript{40} which could explain why the conclusion of Ota et al. differs from the current conclusions. In Tahan et al., the sample included participants of both genders. However, the participants ranged in age from 18 to 44 years of age. As revealed in other studies\textsuperscript{40,41} investigating age-related changes in muscles mass, the age effect on TrA thickness can occur later in life, most probably over 50 years of age. Moreover, as people become less involved in func-

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### Table 3. Spearman’s $\rho$ correlation coefficients for myofascial structures and TrA activation with age

<table>
<thead>
<tr>
<th>Muscle thickness (mm)</th>
<th>Correlation coefficients</th>
<th>95% CI</th>
<th>$p$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO</td>
<td>-0.66</td>
<td>[-0.77; -0.50]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>IO</td>
<td>-0.51</td>
<td>[-0.66; -0.32]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TrA</td>
<td>-0.58</td>
<td>[-0.70; -0.42]</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fascia thickness (mm)</th>
<th>Correlation coefficients</th>
<th>95% CI</th>
<th>$p$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEO</td>
<td>0.39</td>
<td>[0.18; 0.56]</td>
<td>0.000</td>
</tr>
<tr>
<td>FIO/EO</td>
<td>0.54</td>
<td>[0.35; 0.68]</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>FIO/TrA</td>
<td>0.74</td>
<td>[0.60; 0.83]</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TrA activation</th>
<th>Correlation coefficients</th>
<th>95% CI</th>
<th>$p$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>TrA AR</td>
<td>-0.44</td>
<td>[-0.60; -0.25]</td>
<td>0.000</td>
</tr>
</tbody>
</table>

EO: external oblique; IO: internal oblique; TrA: transversus abdominis; FEO: fascia superior to the external oblique; FIO/EO: fascia between internal oblique and external oblique; FIO/TrA: fascia between internal oblique and transversus abdominis; TrA AR: transversus abdominis activation ratio. Level of significance = $p<0.05$. 

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in relation to age, using US imaging assessments. These results demonstrate that normal aging is associated with changes in deep abdominal myofascial structures and TrA activation. The participants’ characteristics show that the sample was similar in terms of age range and proportion of men and women to the population used by Rankin et al.,\textsuperscript{36} who published one of the most definitive studies on normal reference values for thickness of the lateral abdominal muscles. They investigated a cohort of 123 participants within the same age range (20 to 72 years); this cohort also had a similar proportion of men vs. women (44% and 64%, respectively). However, the authors reported higher mean muscle thickness values for EO (6.7 mm), IO (10.2 mm) and TrA (0.50). Rankin et al. used the anterior superior iliac crest as a landmark, whereas we used the posterior rim of the thoracolumbar fascia. Therefore, the probe position used in the current study might have been slightly more posterior. This could explain the difference between the two studies. However, the mean muscle thickness values are close to those of Tahan et al.,\textsuperscript{10} who also investigated a large cohort of healthy participants (n=156) comprised of 75 men and 81 women. A similar pattern in order of thickness for the lateral abdominal muscles as reported in previous studies was found (i.e. IO>EO>TrA).\textsuperscript{10,36,37} With regard to the difference in muscle thickness by sex, the current results show that men have greater muscle thickness than women, which is in accordance with the findings of other studies.\textsuperscript{10,12,36} The TrA AR values of the present study are slightly lower than those reported by Stetts et al.\textsuperscript{29} and by Teyhen et al.,\textsuperscript{11} but they are similar to those reported by Gorbet et al.\textsuperscript{38} However, comparison between studies is difficult due to the specificity of the population studied: Gorbet and Teyen involved only younger participants, whereas Stetts’ sample was composed of older adults only. Moreover, studies’ heterogeneity in the instructions given to the participants to contract their TrA or in the maneuver the participants had to perform might have led to different level of muscle activation. The maneuver used in the present study and in Gorbet’s study is normally executed at low force level and TrA activation measured with US imaging has been shown to correlate to EMG recordings.\textsuperscript{14}
stimulation, their TrA may be engaged less. Although the relationship for TrA atrophy with decreased activities was demonstrated in Ikezoe et al.,\textsuperscript{18} data on the physical activity level of the participants in the present study would be needed to confirm this assertion.

Interestingly, a positive correlation with age was found for all fasciae associated with the three abdominal muscles. Whittaker et al.\textsuperscript{12} did not find a significant correlation with age, but as mentioned, their fascia variable was defined as the sum of the FEO/IO, FIO/TrA and FTrA (posterior fascial layer of the TrA) in contrast to the present study, which considered different fascial layers (FEO, FEO/IO and FIO/TrA). The population in Whittaker et al. was composed of much younger participants and the effect of older age on connective tissues might not have been captured. Since the association with age was not the primary research question, the sample size was probably not large enough to have sufficient power for a correlation analysis. Fan et al.\textsuperscript{39} did not find a correlation with age but again, methodological considerations make comparisons with the results difficult, given that the fascia thickness was measured differently and that the sample was composed of women of younger age.

The present study is the first to investigate the relationship between TrA activation and age while considering both the muscle and the fascia components. The results from the bivariate analyses showed that TrA activation decreases with age. Other studies have found either an increase in abdominal muscle activation or a decline in activation with age. This discordance can be explained by methodological differences (i.e., these studies were not TrA specific, muscles’ activations measurements via EMG during different tasks).\textsuperscript{20–22} However, the strength of the correlation was moderate, indicating that TrA activation is explained by other factors. The results of the hierarchical regression analyses support this assertion, demonstrating that demographic factors such as age (19.5%) and gender explained 23.1% of TrA activation. Adding structural factors such as TrA muscle and fascia thickness indicated that these factors did not significantly explain TrA activation. Although the current results support that TrA and fascia change with age, the authors’ assumption that these structural modifications could impair TrA activation cannot be supported by the results of the present study. One possible explanation for this is that thickening of the epimysial fascia might not alter TrA activation, but thickening of intramuscular fascia (perimysium and endomysium) as seen in aging might do so.\textsuperscript{42,43} Therefore future US imaging studies could explore, for example, the percent of echogenicity (number of black and white pixels) of the TrA to better understand the role that intramuscular fascia might have on muscle activation. Moreover, normal aging is a multifactorial process involving not only modifications of myofascial structures but also a progressive decline of various organ systems, including the central and autonomous nervous systems, as well as potentially less time spent in standing and being involved in physical activity.\textsuperscript{44,45} All of these factors can have an impact on activation capacity of the TrA.\textsuperscript{46} Additionally, changes in TrA activation might be related to adapted breathing function: older people may need less oxygen, may breathe more superficially or use less of a TrA activation range. This raises a very interesting question: Could age-related TrA activation be a natural process without negative consequences?

**STUDY LIMITATIONS**

The results of the present study cannot be generalized to symptomatic populations since factors such as pain, spinal pathologies and deconditioning have an impact on myofascial structures and muscle activation that go well beyond.

### Table 4. Hierarchical linear regression with TrA AR as the dependant variable

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>R²</th>
<th>Adjusted R²</th>
<th>Standardized β</th>
<th>b</th>
<th>S.E.</th>
<th>p</th>
<th>95% C.I. for b</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>0.195</td>
<td>0.185</td>
<td>-0.441</td>
<td>-0.006</td>
<td>0.001</td>
<td>0.00</td>
<td>[-0.009; -0.003]</td>
</tr>
<tr>
<td><strong>Model 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-0.438</td>
<td>-0.006</td>
<td>0.001</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>0.230</td>
<td>0.212</td>
<td>0.189</td>
<td>0.106</td>
<td>0.054</td>
<td>0.05</td>
<td>[-0.001; 0.231]</td>
</tr>
<tr>
<td><strong>Model 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-0.469</td>
<td>-0.007</td>
<td>0.002</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>0.205</td>
<td>0.115</td>
<td>0.058</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TrA thickness</td>
<td>0.232</td>
<td>0.204</td>
<td>-0.054</td>
<td>-0.018</td>
<td>0.043</td>
<td>0.67</td>
<td>[-0.104; 0.068]</td>
</tr>
<tr>
<td><strong>Model 4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-0.600</td>
<td>-0.008</td>
<td>0.002</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>0.197</td>
<td>0.110</td>
<td>0.058</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TrA thickness</td>
<td>-0.070</td>
<td>-0.024</td>
<td>0.043</td>
<td>0.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIO/TrA</td>
<td>0.246</td>
<td>0.209</td>
<td>0.171</td>
<td>0.158</td>
<td>0.128</td>
<td>0.22</td>
<td>[-0.097; 0.413]</td>
</tr>
</tbody>
</table>

TrA: transversus abdominis; FIO/TrA: fascia between internal oblique and transversus abdominis; S.E.: standard error. Level of significance = p<0.05.
those of normal aging. Although measurement of lateral abdominal muscles is now recognized as valid and reliable, measurement of fascia thickness is a new field. Radiological anatomy studies support that the fascia can be measured with US imaging, but the reliability of these measurements has only been reported in one study which neglected to take participant variability into account. Nevertheless, we believe that the method used (i.e. taking the mean of three measurements at equidistant intervals within 1.2 cm) reduced intra- and inter-operator variability and may be more robust than taking only one measurement. Sliding of the TrA as done by Chen et al. would have provided useful information about age-related muscle-fascia dynamics. These results cannot be generalized to adults with chronic diseases or conditions. Lastly, as previously mentioned, other factors such as level of physical activity involving recruitment of the TrA or factors related to the functioning of the central and autonomous system during TrA activation or to breathing pattern would have provided valuable additional information to predict decline in TrA activation with age.

CONCLUSION

The results of the present study demonstrate that normal aging is associated with changes in myofascial structures and TrA activation. These results can serve as reference values for sport physical therapists involved in rehabilitation or in strengthening programs for older healthy individuals. Assessing these metrics with US imaging can provide valuable baseline values that can be used to monitor the effect of these programs. Age and gender are good predictors of TrA activation, but other factors should be considered to complement the understanding of the very complex nature of TrA activation.

CONFLICT OF INTEREST

All authors confirm that no prior or duplicate publication has been released elsewhere concerning this manuscript and that no commercial relationships which may lead to conflict of interest were associated with this work.

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Background
Overuse injury is a common stressor experienced by female collegiate athletes and is often underreported. In response, athletes may develop negative coping skills such as substance use. Alternatively, resilience is a modifiable trait that may positively influence response to musculoskeletal injuries and substance use.

Purpose
To provide an updated epidemiological profile of overuse injury and substance use and examine the relationship between resilience, overuse injury, and substance use among collegiate female athletes.

Design
Cross-sectional study

Methods
Two-hundred and thirty female collegiate athletes were classified into overuse injury and resilience groups. Overuse injury, pain, and substance use incidence proportions (IP) were calculated. Kruskal-Wallis analyses were performed to investigate differences in substance use among resilience groups. Analyses of covariance were performed to evaluate differences in overuse injuries, substantial overuse injuries, and time loss injuries, among resilience groups.

Results
IP for pain was 45.0% (95% CI: 38.2-51.9); Overuse injury 52.0% (45.1-58.9); Alcohol use 35.1% (28.6-41.6); Electronic cigarette use 19.5% (14.6-24.9); Cigarette use 2.8% (6-5.1); and Drug use 3.3% (0.9-5.8). No significant differences were found between resilience groups for the Oslo Sports Trauma Research Center Overuse Injury Questionnaire (OSTRC) variables (Pain: p=0.102; Overuse injury: p=0.331; Substantial overuse injury: p=0.084; Not playing: p=0.058), alcohol (p=0.723), or combined substance use (p=0.069).

Conclusions
Pain and overuse injury prevalence is high among female collegiate athletes. Alcohol followed by electronic cigarette use were the most commonly utilized substances. No significant differences were identified in substance use or overuse injury presentation.
between resilience groups, though further investigation is warranted.

**Level of Evidence**

**INTRODUCTION**

The National Collegiate Athletic Association regulates and organizes sports for 1,200 colleges and universities, and consists of division one (D1), two (D2), and three (D3) programs. Female participation in collegiate sports has increased in recent decades, with the number of female teams now surpassing men’s teams. Across all divisions, sport participation exposes female collegiate athletes to a substantial amount of stress, in order to meet the demands of being a student-athlete. Stress can be defined as a state of perceived imbalance between demand and available coping resources, and can come from sources such as relationships, academic responsibilities, or physical challenges such as poor performance and injury. When considering physical stressors, overuse injuries are a possible stressor resulting from progressive microtrauma with no specific identifiable event and inadequate recovery. The prolonged onset and longitudinal nature of overuse injuries expose student athletes to additional stress. Recent epidemiological data demonstrates that female collegiate athletes have a higher overuse injury rate compared to male athletes (24.6 versus 13.2 per 10,000 athlete exposures). In the same study, the authors reported that 50.8% of overuse injuries did not result in time loss from sport. Thus, using standard time loss definitions for injury surveillance, along with the higher rate of overuse injuries in females, may contribute to injury underreporting among female collegiate athletes.

Due to current injury classification and reporting method limitations, the Oslo Sports Trauma Research Centre (OSTRC) designed the Overuse Questionnaire (OSTR C) to capture the spectrum of overuse symptoms and consequence on participation, training, and performance. Early research has indicated that the OSTR C captures over ten times as many overuse conditions compared to time-loss definitions. Using the OSTR C, adolescent female gymnastic, basketball, and volleyball athletes reported 8.6 overuse injuries per 1000 athlete exposures; in a separate study using standard injury definitions, adolescent female athletes participating in the same three sports reported substantially lower rates of injury, 1.76-2.74 per 10,000 athlete exposures. Among female athletes, updated injury epidemiological data that reflects the spectrum of overuse conditions is essential; thus the OSTR C may allow for improved quantification and understanding of overuse injury burden in this population.

In order to manage sport related stressors such as overuse injuries, athletes may use a variety of coping strategies. Traditional coping strategies employed by collegiate students include academic support, social support, leisure activities, sport and fitness participation or participation in risk prone activities (i.e. alcohol and other substance use). Injured student-athletes have fewer options to manage their stress due to participation limitations and variable social support. Substance abuse, has been identified as a negative coping strategy. Misuse of substances by athletes including alcohol, cigarettes, and illicit drugs has been documented in previous studies. Misuse of substances has been associated with an array of health, social, academic, and performance consequences. Acute health consequences of illicit drug and alcohol use include acute toxic effects, such as overdose, and accidental injury and harm; chronic effects from sustained use include dependence, development of chronic diseases, and increased likelihood of developing mental disorders. With regard to cigarettes, chronic use has demonstrated associations with cardiovascular disease, chronic obstructive pulmonary disease and various cancers. During the 1990s, multiple studies were conducted on alcohol, tobacco, and drug use among college students, but peer-reviewed literature has been sparse in the last 20 years among collegiate athletes. Further, a new delivery mechanism for substance use, the electronic cigarette, has shown increased use among college adults.

Although electronic cigarettes were originally marketed as a smoking cessation tool, use has increased among nonsmokers despite sparse data on longitudinal health impacts. Epidemiological substance use data is needed to inform sports medicine, coaching, and support personnel about the negative coping strategies in female collegiate athletes. In contrast to negative coping skills, positive coping skills may be utilized by athletes. Resilience is a psychological property that has been associated with positive coping skills such as optimism, interconnectedness with social support systems, and higher self-esteem. Resilience has been conceptualized in various ways, but a common definition is the ability to bounce back despite the presence of stressors. Resilience is recognized as a personality trait that can change over time, and may be modified through intervention programs. Resilience has been observed to have a positive influence on the management of chronic pain, osteoarthritis, and following joint replacement surgery. Further, high levels of resilience are associated with decreased substance use in nonathlete populations. Nevertheless, research on athlete resilience has not investigated the relationship of resilience on musculoskeletal health or substance use. Due to stress experienced among collegiate athletes, resilience may be an important, modifiable characteristic. Specifically, resilience potentially can promote positive coping skills for in the presence of an overuse injury or to minimize negative coping skills such as substance use.

Therefore, the purpose of this study was to provide an updated epidemiological profile of overuse injury and substance use and examine the relationship between resilience, overuse injury, and substance use among collegiate female athletes. Additionally, this study examined the relationship between resilience, overuse injury and substance use among this population.
METHODS

STUDY DESIGN

This study was a cross-sectional design that was a subset of a larger study including male and female athletes which sought to investigate collegiate athlete health and well-being. The study included athletes participating in D1, D2 and D3 institutions. The study was approved by the Elon University Institutional Review Board (ID: 20-026).

PARTICIPANTS AND RECRUITMENT

The questionnaire was administered by the sports medicine staff to current collegiate athletes via email. Study consent was provided by clicking on the email link which provided a copy of the institutional review board consent form prior to completing the questionnaire with assurance of anonymity. The data were managed and de-identified to ensure anonymity using Qualtrics (Qualtrics, Provo, UT), an online survey database. Data collection occurred over eight weeks from August through September 2019. To reduce participant burden, athletes could save responses and complete the questionnaire at any time during the eight week period. Two reminder emails were sent at week two and week six, and coaches gave verbal reminders during week four to increase participation. Inclusion criteria consisted of: 1) enrollment at a participating institution; 2) listed on the official roster of their sport; 3) university email on file with the athletic department. Exclusion criteria consisted of: 1) no consent given to complete the questionnaire; 2) club or recreational collegiate athletes; or 3) no longer participating in varsity collegiate athletics.

QUESTIONNAIRE DESIGN

The questionnaire was designed to capture several aspects of health and well-being among collegiate athletes. The aspects of health and well-being investigated included: 1) athlete general health; 2) lifestyle and academics; 3) pain, injury, and surgery; and 4) well-being. The questionnaire used in this study was adapted from a cricket health and well-being study and was refined following interviews with three collegiate athletes, two collegiate coaches, one collegiate athletic trainer, two collegiate physical therapists, and one sports medicine physician to identify health and well-being issues pertinent to collegiate athletes. The questionnaire was piloted with all the professionals and the athletes were interviewed for final format adaptations. The questionnaire inquired about demographic information including athlete age, height, weight, sports participation, injury history, alcohol and substance use, sleep habits, and health related quality of life. All data were managed and de-identified via Qualtrics software (Qualtrics, Provo, Utah).

MAIN OUTCOME MEASURES

ALCOHOL, CIGARETTE, ELECTRONIC CIGARETTE AND DRUG USE

Alcohol use was determined using questions from the Harvard College Alcohol Study (CAS). Participants were asked the following question: “Have you drank alcohol in the past 30 days?” If the participant answered yes, they were asked to fill out a series of questions that included the following: 1) How many occasions have you had alcohol in the past 30 days? Participants could select 1 to 2, 3 to 5, 6 to 9, 10 to 19, 20 to 29 or 40+ occasions as a response. 2) How important is getting drunk as a reason to drink? Answer choices included Very Important, Important, Somewhat Important, Not at all Important. For the remaining questions, participants typed their answers in a text box to respond: 3) How many occasions in the past 30 days did you drink enough to get drunk? 4) How many times have you missed class as a result of drinking? 5) How many occasions have you consumed alcohol in the last 7 days? 6) How many consecutive drinks did you consume during those occasions? Heavy drinking style was defined as 10 or more drinking occasions in the last 30 days, a motivation to drink to get drunk of somewhat to very important, getting drunk three or more times in the past 30 days, or four or more consecutive drinks in one occasion in the past week.

To determine tobacco use, questions that captured cigarette use from the Harvard CAS were used. The first question was “Have you ever smoked cigarettes before?” If the participant answered yes, they were asked a series of follow up questions that included: 1) How old were you when you first smoked? Answers were typed in a text box. 2) When did you most recently smoke? Answer choices included Never, More than 12 months ago, More than 30 days ago but less than 12 months ago, Less than 30 days ago. 3) Do you smoke regularly? Participants responded yes or no. If the participant answered yes, they were asked 4) How many times a day? Responses were typed in a text box. Tobacco use questions did not cover smokeless tobacco in this study.

To determine electronic cigarette use, questions determining electronic cigarette use from the Harvard CAS were adapted. The participants were asked the following question: “Have you ever used e-cigarettes or a vape pen?” If the participant answered yes, the following series of questions were asked: 1) How old were you when you first used e-cigarettes or a vape pen? Participants typed their answer in a text box to respond. 2) When did you most recently use e-cigarettes or a vape pen? Answer choices included Never, More than 12 months ago, More than 30 days ago but less than 12 months ago, Less than 30 days ago. 3) Do you use e-cigarettes or a vape pen regularly? Participants responded yes or no. If the participant answered yes, they were asked 4) How many times a day? Responses were typed in a text box.

Drug use was captured using the Harvard CAS drug survey questions with the following question: Have you used any recreational drugs within the last 30 days? If the participant answered yes, they were prompted in the next question to indicate frequency: How frequently do you use them? The participants typed their answers in a text box.

THE OSLO SPORTS TRAUMATIC RESEARCH CENTER FOR OVERUSE INJURY QUESTIONNAIRE

The OSTRC was used to determine the presence of an overuse injury and their effect on sports performance and training. The OSTRC has been used in a variety of athletic populations, and demonstrates good validity and reliability.
with an internal consistency of $\alpha = 0.91$.\textsuperscript{6} The questionnaire consists of four questions asking the patient to indicate levels of pain and the impact of pain and injury on sports participation, training volume, and performance. Each question is based on a scale of 0-25 with 0 indicating no overuse injury problem and 25 indicating a severe overuse injury problem. Questions 1 and 4 were scored on a scale of 0-8-17-25 and questions 2 and 3 were scored on a scale of 0-6-13-19-25. The values utilized indicate a score of 0 representing no problems, whereas a score of 25 represents the maximum level of problems for each question. The intermediate values are scored as such to allow an even distribution from 0-25. The questions were summed for a total score out of 100.

Participants with and without an overuse injury problem were identified by using total OSTRC score, and categorizing participants into overuse injury (total OSTRC score>0) or no overuse injury (total OSTRC score = 0) groups. Participants with and without pain were identified by calculating question 4 scores only (to what extent have you experienced pain in the last week), and categorizing participants into pain (score >0) and no pain (score = 0) groups. To identify severe overuse problems, participants were further categorized into substantial overuse injury (score = 25-39) or no substantial overuse injury (score >0 and <25), and not playing (score >40) or playing (score <40) groups to differentiate levels of severity of an overuse problem.\textsuperscript{6}

RESILIENCE

Resilience was assessed using the Brief Resilience Scale (BRS). The BRS has previously demonstrated high test-retest reliability and validity.\textsuperscript{26} The BRS consists of six questions that are scored from 1 to 5. Questions are alternated, such that the most resilient response for odd numbered questions is 5 points and for even questions is 1 point. When scored, the even numbered questions are reversed, and all answers are summed for a total possible score of 6 (low resilience) to 30 points (high resilience). Normative data for BRS scores among athletic populations was not available in the peer reviewed literature. Therefore, to determine differences among participants with high or low resilience scores, the mean and standard deviation (SD) of BRS scores were calculated.\textsuperscript{31} Participants who scored 1 SD below the mean were classified as the low resilience group (LR), those with scores within 1 SD of the mean were classified as the normal resilience group (NR), and participants who scored greater than 1 SD above the mean were classified as the high resilience group (HR) for statistical analysis.

STATISTICAL ANALYSES

Missing data were analyzed through counts, percentages, and visualization through the R package naniar (R Core Team, 2015; R: A language and environment for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/). Missing data was varied (Age <1%, Resilience 7%, OSTRC 12%, Alcohol last 30 days 9%, Number of alcohol occasions 69%, Importance of getting drunk 10%, Occasions of getting drunk 70%, Combined E-Cig, Cigarette, and Drug use 8-9%, Frequency of E-Cig, Cigarette, or Drug Use >70%). A complete case analysis was performed. However, due to the varied degrees of missing data, only questions with ≤10% missing data were statistically analyzed in order to reduce bias. Descriptive data were reported as mean (SD), median (interquartile range), or count (%). Sport participation was categorized as individual (cross-country, track and field, triathlon, swimming, golf, and dance), field and court (basketball, soccer, tennis, and volleyball), bat and ball (baseball and softball), and collision (football, rugby, and lacrosse).\textsuperscript{56} Overuse injury, pain, alcohol, e-cigarette, cigarette and drug incidence proportions (IP) with 95% confidence intervals (95% CI) were calculated using the following formula:\textsuperscript{37}

$$\text{Variable IP} = \frac{\text{No of athletes presenting with variable}}{\text{No of all athletes}} \times 100$$

Injury and surgery history prevalence was calculated for all female athletes and for each resilience group. A series of Kruskal-Wallis analyses were performed to investigate potential differences between alcohol and amalgamated substance use and resilience groups. An analyses of covariance (ANCOVA) was performed to evaluate potential differences between current overuse injuries, substantial overuse injuries, and time loss injuries, evaluated by the OSTRC, and resilience groups. Confounders controlled for included injury in the prior four weeks and surgery history (p<0.05). All statistical analyses were performed in R version 3.5.1.

RESULTS

One thousand, two hundred and thirty-nine male and female athletes received the survey. Participant recruitment is illustrated in Figure 1. A total of 230 female athletes (38% response rate) completed the questionnaire and were included in the study (D1: n = 89, 39% response rate; D2: n = 77, 33% response rate; D3: n = 64, 28% response rate). Median age of participants were 19 years (18-20), and the greatest number of participants participated in field and court sports (45.3%). 51.9% reported a new injury but no recent surgery (14.8%). (Table 1)

<table>
<thead>
<tr>
<th>Injury</th>
<th>IP (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain and overuse injury</td>
<td>45.0% (95% CI: 38.2 to 51.9)</td>
</tr>
<tr>
<td>Pain and overuse injury</td>
<td>52.0% (95% CI: 45.1 - 58.9)</td>
</tr>
</tbody>
</table>

Among all substances, both groups reported similar alcohol use IP was 35.1% (95% CI: 28.6 - 41.6); electronic cigarette use IP was 19.5% (95% CI: 14.6 - 24.9); cigarette use IP was 2.8% (95% CI: 0.6 - 5.1); and drug use IP was 3.3 (95% CI: 0.9 - 5.8).

BRS scores ranged from 10 to 30 points, with a mean of 21.3 (4.2). 26.2% of participants (n=48) were classified as LR, 60.7% (n=111) as NR, and 13.1% (n=24) as HR. Nearly a third of all athletes reported an overuse injury (HR: 41.7%, LR: 28.7%), but fewer substantial overuse injuries (HR: 10.5%, LR: 8.3%) or inability to play (HR: 8.3%, LR: 10.5%).

No significant differences were found between resilience groups for any OSTRC variables (Pain: p = 0.11; Overuse injury: $\chi^2 = 2.214$, p = 0.54; Substantial overuse injury: $\chi^2 = 4.962$, p = 0.09; Not playing: $\chi^2 = 5.667$, p = 0.06).

Among substances, both groups reported similar alcohol use in the last 30 days (HR: 29.1%, LR: 35.4%) and drinking to get drunk as important (HR: 4.2%, LR: 8.3%) (Table 2). No significant differences between resilience groups for alcohol use were found. (Table 2)
questions were found (Alcohol last 30 days: $\chi^2 = 0.652, p = 0.73$; Drink to get drunk important: $\chi^2 = 5.747, p = 0.06$). Electronic cigarette use was more prevalent in LR group (31.3%) versus HR group (8.3%), but cigarette and drug use prevalence were similar between groups (Cigarette- HR: 0%, LR: 2.8%; Drug- HR: 0%, LR: 4.2%; Table 2). No significant difference was found between resilience groups and overall substance use ($\chi^2 = 5.356, p = 0.07$).

**DISCUSSION**

The findings of this study indicate that pain and overuse injury is a common adverse event that female collegiate athletes experience. Further, alcohol and electronic cigarette use were the most common substances used. While available research indicates that resilience may play a role in decreased substance use and musculoskeletal health in non-athlete populations, the current study’s findings did not demonstrate this relationship.

The results of this study demonstrated that across all sports, 45 out of 100 female athletes reported pain and 52 out of 100 reported an overuse injury, representing a sizable portion of the population. This finding corroborates existing research on incidence proportion among female athletes when using the OSTRC as a measure to capture pain and overuse injuries. However, the OSTRC has not been widely used among intercollegiate athletes in the United States. When compared to standard methods of injury classification, such as time-loss or need for medical attention, the results of this study suggest that standard injury classification methods are not capturing the spectrum of overuse problems that are impacting athlete performance, overall health and well-being. Additionally, female collegiate athletes have a higher risk of overuse injuries compared to males, and differences in pain response have been reported among males and females, though the exact cause is unknown. These differences in injury presentation and pain response between male and female athletes highlights a need for further exploration among mechanisms of pain and overuse injury in the female athlete population.

Among substances, alcohol was the most prevalent with more than one in three athletes indicating alcohol use in the past 30 days. Comparatively, previous national surveys have asked participants to indicate alcohol use over the past year. Prevalence rates in 1997 and 2001 were 86.0% and 80.8% respectively among female athletes; in more recent years among college aged adults, prevalence rates were 70.8% and 78% in 2001-2002 and 2012-2013, though female collegiate athlete prevalence was not determined. The current study’s lower prevalence compared to previous research may be due to several factors. First, this study is reflective of a smaller time frame captured; athletes in their competitive seasons are more likely to abstain from drinking, and therefore prevalence may be underestimated. Additionally, females have consistently demonstrated lower alcohol consumption overall compared to males, though this study did not seek to compare between males and females. Further, lower consumption may reflect policy changes following the Harvard CAS, including resolutions passed in Congress calling for university presidents to address heavy alcohol use, and the United States Surgeon
Table 2. Resilience and Substance Use Profile

<table>
<thead>
<tr>
<th>OSTRC Variables</th>
<th>Overall</th>
<th>Low Resilience</th>
<th>Normal Resilience</th>
<th>High Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OSTRC Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pain Yes</td>
<td>91 (45.0%)</td>
<td>23 (47.9%)</td>
<td>44 (39.6%)</td>
<td>12 (50%)</td>
</tr>
<tr>
<td>Pain No</td>
<td>111 (55.0%)</td>
<td>25 (52.1%)</td>
<td>67 (60.4%)</td>
<td>12 (50%)</td>
</tr>
<tr>
<td><strong>Overuse Injury Severity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Injury</td>
<td>97 (48.0%)</td>
<td>22 (57.9%)</td>
<td>59 (53.2%)</td>
<td>9 (37.5%)</td>
</tr>
<tr>
<td>Overuse Injury</td>
<td>58 (28.7%)</td>
<td>11 (28.9%)</td>
<td>31 (27.9%)</td>
<td>10 (41.7%)</td>
</tr>
<tr>
<td>Substantial Overuse</td>
<td>20 (9.9%)</td>
<td>4 (10.5%)</td>
<td>11 (9.9%)</td>
<td>2 (8.3%)</td>
</tr>
<tr>
<td>Not Playing</td>
<td>27 (13.4%)</td>
<td>11 (28.9%)</td>
<td>10 (9.0%)</td>
<td>3 (12.5%)</td>
</tr>
<tr>
<td><strong>Alcohol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Last 30 days Yes</td>
<td>73 (35.1%)</td>
<td>17 (35.4%)</td>
<td>42 (37.8%)</td>
<td>7 (29.1%)</td>
</tr>
<tr>
<td>Last 30 days No</td>
<td>135 (64.9%)</td>
<td>31 (64.6%)</td>
<td>69 (62.2%)</td>
<td>17 (70.8%)</td>
</tr>
<tr>
<td>Number of Occasions Last 30 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 or more</td>
<td>1 (1.5%)</td>
<td>1 (5.9%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Less than 10</td>
<td>65 (98.5%)</td>
<td>16 (94.1%)</td>
<td>42 (100%)</td>
<td>7 (100%)</td>
</tr>
<tr>
<td>Number of Occasions Drunk Last 30 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 or more</td>
<td>8 (13.1%)</td>
<td>4 (25.0%)</td>
<td>4 (10.5%)</td>
<td>-</td>
</tr>
<tr>
<td>Less than 3</td>
<td>53 (86.9%)</td>
<td>12 (75.0%)</td>
<td>34 (89.5%)</td>
<td>7 (100%)</td>
</tr>
<tr>
<td>Number of Consecutive Drinks Last 7 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 or more drinks</td>
<td>22 (13.6%)</td>
<td>9 (19.6%)</td>
<td>8 (8.3%)</td>
<td>5 (25.0%)</td>
</tr>
<tr>
<td>Less than 4 drinks</td>
<td>140 (86.4%)</td>
<td>37 (80.4%)</td>
<td>88 (91.7%)</td>
<td>15 (75.0%)</td>
</tr>
<tr>
<td><strong>Importance of Getting Drunk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Somewhat Important - Very Important</td>
<td>30 (16.4%)</td>
<td>4 (8.3%)</td>
<td>2 (1.8%)</td>
<td>1 (4.2%)</td>
</tr>
<tr>
<td>Not Important at All - Do Not Drink</td>
<td>176 (83.6%)</td>
<td>44 (91.7%)</td>
<td>109 (98.2%)</td>
<td>23 (95.8%)</td>
</tr>
<tr>
<td><strong>E-Cigarettes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>41 (19.5%)</td>
<td>15 (31.3%)</td>
<td>21 (18.9%)</td>
<td>2 (8.3%)</td>
</tr>
<tr>
<td>No</td>
<td>169 (80.5%)</td>
<td>33 (68.8%)</td>
<td>90 (81.1%)</td>
<td>22 (91.7%)</td>
</tr>
<tr>
<td><strong>Smoking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>6 (2.8%)</td>
<td>3 (4.3%)</td>
<td>2 (1.8%)</td>
<td>-</td>
</tr>
<tr>
<td>No</td>
<td>205 (97.2%)</td>
<td>45 (93.6%)</td>
<td>109 (98.2%)</td>
<td>24 (100%)</td>
</tr>
<tr>
<td><strong>Drugs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>7 (3.3%)</td>
<td>2 (4.2%)</td>
<td>3 (2.7%)</td>
<td>-</td>
</tr>
<tr>
<td>No</td>
<td>203 (96.7%)</td>
<td>46 (95.6%)</td>
<td>108 (97.3%)</td>
<td>24 (100%)</td>
</tr>
</tbody>
</table>

OSTRC = Oslo Sports Traumatic Research Center Overuse Injury Questionnaire; Data are reported as a count (%)

Differences in count data between overall and resilience groups are due to missing data

General documented goal of reducing binge drinking by 50% in 2010. However, peer-reviewed research on alcohol use among collegiate athletes have been sparse since the Harvard CAS, making it difficult to confirm impact of policy changes and shift in drinking culture among collegiate athletes.

Heavy drinking style is a concern among college athletes. Collegiate athletes are more likely to experience alcohol related harms compared to non-athletes, and are uniquely at risk for sports performance consequences. In this study, heavy drinking style prevalence as measured independently by frequency, intensity and motivation to get drunk was lower than previous studies of all college students. However, these findings should be interpreted with caution due to the high percentage of missing data. Previous research has indicated that while college-aged males consume the most alcohol among sex and age groups, females are demonstrating a sharper increase in consumption and heavy episodic drinking, narrowing the gender gap. This sharp increase among females may be associated with a continued increased rate of females pursuing college level degrees and further economic opportunities, providing a framework for increased exposure and permissive attitudes for heavy drinking.
drinking behaviors among athletes has been sparse in the last 10 years, and substantially more data is needed to expand on our findings to determine accurate prevalence of heavy drinking style among female athletes and related health consequences. Only 2.8% of participants reported cigarette use, a finding that demonstrates continued decrease in tobacco use among college athletes and nonathletes since the 1990s.20,44 This decrease may be attributed to research, public education, and regulation efforts highlighting the risk of cardiovascular and lung disease as well as perceived negative performance consequences.44,45 Additionally, participation in collegiate athletics has demonstrated a protective effect against tobacco use compared to non-athletes.45 Drug use was also low at 3.3% and corroborates previous research indicating that an inverse relationship between participation in sport and drug use exists.44 In 2001, marijuana use in the past 30 days among college students was 16.9% and even lower for all other illicit drugs (7.57%), much higher than what the current study demonstrates among female athletes.19 Our lower prevalence findings may be reflective of athlete awareness on the deleterious effects of drug use on performance, but given a lower response rate on drug related questions (>70%), further research is needed to confirm these findings.44 Additionally, collegiate athletes are susceptible to random drug testing throughout the year from the NCAA and individual institutions. While studies on impact of drug testing on substance use among collegiate athletes is limited, previous research among high school athletes has indicated that random notification drug testing curtailed substance use short term, and therefore may have similar effects among college athletes.46

Interestingly, prevalence of electronic cigarette use was much higher compared to cigarette and drug use; nearly one in five female athletes reported using this delivery mechanism for substances. While data on athlete use is sparse, this represents a much higher prevalence compared to recent use of adults over 18 years old from 2012 to 2013 (1.4-6.8%).24 Electronic cigarette use has not demonstrated the same inverse relationship with sports participation compared to cigarette and drug use.47 A lack of longitudinal research on adverse health and performance effects,24 a shift in marketing strategies geared towards younger consumers,25 and fewer regulations in public spaces compared to tobacco products may contribute to perceptions that the product is a safe alternative to cigarettes.39 This assumption of safety may reflect the higher prevalence among the current study’s cohort and sharp increase in use among adults since the product entered the market in 2006.24 Electronic cigarettes contain toxicants and nicotine24 and early studies indicate increased likelihood of future cigarette use to be linked with use of electronic cigarettes.47 Additionally, electronic cigarette use has been marketed as a smoking cessation tool, and early evidence indicates that a majority of electronic cigarette users have smoked cigarettes.23 Given that the vast majority of the participants in the current study did not report cigarette use, further research is needed to understand motivational factors related to electronic cigarette use in the female collegiate athlete population. Additionally, further research is needed to determine the longitudinal health effects of electronic cigarettes.

Little attention has been paid to the impact of psychometric properties such as resilience on musculoskeletal health. While pain and overuse injury represent one of many stressors an athlete faces,39 the presence of higher resilience was not associated with differences in pain and overuse injury in this study. Early research has indicated that resilience may have a positive influence on patients with chronic pain,29 osteoarthritis30 and following joint replacement surgery.31 Contrary to these results, this study demonstrated no difference in overuse injuries among different resilience levels in female collegiate athletes. Further research is needed to determine if resilience as a unitary construct is useful to monitor in female athletes, or if additional psychometric properties should be considered to influence overuse injury outcomes. Among substances, differences in use were not determined between resilience levels in the participants. Increased substance use has been cited as a potential negative coping strategy for sport-related pressure and anxiety, including coping with pain, injury, retirement, and performance.18 While substance use may be used as a coping strategy among athletes, the lack of association with resilience among the current study findings suggests other explanations may be warranted such as team social dynamics, sorority membership, substance use prior to college, or polydrug use.20 However, research on resilience and substance use is still merited given the low percentage of participants that indicated heavy episodic drinking, drug and cigarette use in this study.

This study is not without limitations. The epidemiological profile reported in this study requires further validation to determine the extent of substance use and impact of using the OSTRC to capture overuse injury data among female collegiate athletes. Secondly, this study captured data at one time point. Longitudinal studies may provide a better understanding of substance use, overuse injury, and resilience fluctuations during in-season and off-season periods to improve knowledge of physical and mental stressors and coping strategies athletes experience. Thirdly, given that this was a cross-sectional study there is the potential for recall bias, especially for substance use in the past month, and there is a possibility that athletes may have underreported their substance use. However, use of previously validated outcome measures for overuse injury, substance, and resilience use were used making the results comparable to previous literature.6,15,20 The current study response rate was 38%, however this response rate is typical for surveys administered among institutions.48 Additionally, given that collision sports were under-represented, and being that the cohort was female only, the results are not generalizable to collision sports or male collegiate athletes. Furthermore, response bias is possible given that athletes interested in study content may be more willing than other athletes to disclose information related to substance or overuse injury. Finally, single method bias is possible given that only an online survey was used to collect data.

**CONCLUSION**

In summary, 45 out of 100 female athletes reported pain
and 52 out of 100 reported an overuse injury, representing a large portion of the population. Regarding recent substance use, alcohol was the most commonly used substance with more than 1 in 3 reporting consumption followed by e-cigarette use at nearly 1 in 5 athletes. The current study findings indicate that resilience did not have any significant associations with pain, overuse injury, or substance use, though further investigation is warranted for associations with heavy episodic drinking and increased data among electronic cigarette, drug, and cigarette use. Notably, given the novelty of electronic cigarettes and high reported use, longitudinal studies on health effects are necessary to provide health education initiatives and information on performance impact. Finally, considering the limitations of current injury definitions to capture injury data, future research should consider use of the OSTRC for further injury surveillance. By improving knowledge on overuse injuries, substance use, and coping strategies, clinicians may be better equipped to provide appropriate interventions and referrals necessary to improve the health and well-being of athletes.

CONFLICT OF INTEREST

None to disclose

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REFERENCES


Original Research

Interprofessional Inconsistencies in the Diagnosis of Shoulder Instability: Survey Results of Physicians and Rehabilitation Providers

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Keywords: multidirectional instability, rotator cuff impingement, shoulder instability, sulcus sign

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Background
Clinicians of many specialties within sports medicine care for athletes with shoulder instability, but successful outcomes are inconsistent. Consistency across specialties in the diagnosis of shoulder instability is critical for care of the athlete, yet the extent of divergence in its diagnosis is unknown.

Hypothesis
Physicians differ from rehabilitation providers in which findings they deem clinically important to differentiate shoulder instability from impingement, and in how they diagnose athlete scenarios with atraumatic shoulder instability.

Study Design
Cross-sectional study.

Methods
Physicians (orthopaedic surgeons, primary care sports medicine physicians) and rehabilitation providers (physical therapists, athletic trainers) were asked via an online survey to rate clinical factors used to diagnose shoulder instability. Clinicians were also asked to diagnose two athlete scenarios with concurrent clinical findings of atraumatic shoulder instability and impingement, differentiated by the absence or presence of a positive sulcus sign.

Results
Responses were recorded from 888 clinicians. Orthopaedic surgeons (N=170) and primary care sports medicine physicians (N=108) ranked physical examination factors as more important for the diagnosis of shoulder instability than patient history factors, whereas physical therapists (N=379) and athletic trainers (N=231) preferred patient history factors. Orthopaedic surgeons differed from physical therapists and athletic trainers in their clinical diagnoses for both scenarios (P<0.001).
Conclusion
A lack of consistency exists among sports medicine clinicians in recognizing which clinical factors are important when used to diagnose shoulder instability and in diagnoses given with concurrent findings of impingement.

Level of Evidence
Level 3.

INTRODUCTION
Shoulder instability, defined as "the loss of shoulder comfort and function due to undesirable translation of the humeral head on the glenoid", affects active individuals such as athletes, military personnel, and manual wheelchair users who use their upper extremity in high-demand activities. Shoulder instability of atraumatic etiology is more difficult to diagnose than traumatic shoulder instability due to the absence of any causal injury. Rehabilitation programs, commonly recommended as first-line treatment for athletes with atraumatic shoulder instability, have produced improved short-term outcomes in terms of pain and function compared to previously established protocols. However, persistent shoulder disability following rehabilitation remains up to eight years after initial diagnosis. Only 69-76% of athletes with atraumatic instability who proceed to surgery after failed rehabilitation return to their respective sports at a pre-injury level.

Inconsistencies in the clinical diagnosis of shoulder instability between clinical specialties within a sports medicine team are suboptimal for comprehensive collaborative care of the athlete. While variation in the diagnosis of atraumatic shoulder instability has been demonstrated among orthopaedic surgeons, the diagnostic criteria used by other specialties within sports medicine, including nonsurgical sports medicine physicians, physical therapists, and athletic trainers, have yet to be explored. Consistency across clinical specialties in the diagnosis of shoulder instability is necessary to coordinate care among all clinicians, any of whom may be the first point of diagnosis or treatment for athletes with shoulder instability. However, differences between sports medicine specialties in clinical training and types of ways through which they interact with injured athletes may affect the uniformity in the criteria used to diagnose shoulder instability.

The purpose of this study was to investigate differences in clinical perspectives among physicians and rehabilitation providers in criteria used to diagnose shoulder instability. We hypothesized that orthopaedic surgeons and primary care sports medicine physicians would differ from physical therapists and athletic trainers in criteria they believe are important to differentiate shoulder instability from rotator cuff impingement. We further hypothesized that sports medicine physicians would differ in how they diagnose athlete scenarios with atraumatic shoulder instability. We tested our hypothesis by administering an online survey to different specialties of sports medicine physicians who diagnose and treat patients with shoulder instability.

METHODS
SURVEY CONTENTS
A survey instrument was created to assess how clinicians interpret varying history and examination findings to diagnose shoulder instability. The survey's content was developed by an interdisciplinary research team that included orthopaedic surgeons, physiatrists, physical therapists, and athletic trainers. The survey was pilot tested among physicians and rehabilitation providers at the institution hosting the study, and suggestions to improve the clarity and functionality of the survey were incorporated. The survey was designed to be completed in 5-10 minutes.

The survey contained two categories of questions regarding the diagnosis of shoulder instability. First, participants rated the importance of fifteen clinical factors that have been described in the literature to be associated with identifying shoulder instability and rotator cuff impingement (Figure 1A). Participants rated each clinical factor on a 5-point Likert scale in its importance to differentially diagnose shoulder instability versus rotator cuff impingement, and each factor was rated independently from all other factors. The fifteen clinical factors were grouped after the survey into patient history factors or physical examination factors. Second, participants were asked to diagnose two athlete scenarios with history and examination findings consistent with atraumatic instability and rotator cuff impingement (Figure 1B). Scenarios 1 and 2 were only differentiated by a negative or positive sulcus sign, respectively. Participants chose from four diagnoses in each scenario such that all were possible diagnoses: secondary impingement, unidirectional instability, multidirectional instability, and other. If a participant chose "other" as a diagnosis for a given scenario, they were prompted to provide a short response describing their alternative choice. Participants were also asked what percentage of their new patients with shoulder pain present with signs and symptoms consistent with scenarios 1 and 2.

Participants were asked to answer additional demographic questions, which included their primary specialty, practice setting, sex, and years of experience practicing within their primary specialty. All survey materials were approved prior to survey distribution by the Institutional Review Board at Northwestern University (STU00207355). Participants answered eligibility screening questions and provided online consent before participating in the study and completed all components using electronic data capture tools (REDCap; Qualtrix). Inclusion criteria were as follows: (i) licensed and/or certified physician, physical therapist, or athletic trainer; (ii) clinician who currently practices in clinical care; and (iii) clinician who treats diagnoses individuals with shoulder instability. Participants
were excluded if they exited the survey prior to completion.

SURVEY DISTRIBUTION

Between October 2018 and June 2019, the finalized survey was emailed to physicians (orthopaedic surgeons, primary care sports medicine physicians) and rehabilitation providers (physical therapists, athletic trainers) through the following professional organizations: American Orthopaedic Society for Sports Medicine (sent to approximately 3316 members), American Shoulder and Elbow Surgeons (856 members), American Medical Society for Sports Medicine (3913 members), American Academy of Physical Medicine & Rehabilitation (3574 members), American Society of Shoulder and Elbow Therapists (111 members), American Academy of Sports Physical Therapy (8500 members), Academy of Orthopaedic Physical Therapy (17592 members), and National Athletic Trainers’ Association (5000 members). Additionally, investigators on the study emailed potential participants and advertised through the social media accounts of departments associated with the host institution. Respondents practicing in emergency medicine, family medicine, internal medicine, pediatrics, and physical medicine & rehabilitation were grouped collectively as primary care sports medicine physicians. Respondents practicing in orthopaedic surgery could indicate if they were a shoulder specialist or practiced within another or no specialty.

STATISTICAL ANALYSES

Data were analyzed using MATLAB statistical packages (version R2020a; MathWorks). Likert-type clinical factor ratings were analyzed as non-parametric statistics. Kruskal-Wallis tests were used to test for differences between all specialties in the rated importance of each clinical factor. If significant group differences were observed, Tukey post-hoc tests were used to evaluate the differences between individual specialties in the rated importance of a single clinical factor. Cross tabulations (4x2 contingency tables) were used to test for differences in scenario diagnosis between specialties (within a scenario) and between scenarios (within a specialty). All statistical tests were evaluated at a significance level of α=0.05 with Bonferroni corrections to control for multiple comparisons.

RESULTS

DEMOGRAPHICS

Responses were recorded from 1202 sports medicine clinicians. The majority (75%; 897/1202) of respondents who indicated they met our inclusion criteria and provided consent to participate in the study proceeded to complete the survey. Nine respondents who indicated that they did not practice within a primary specialty of orthopaedic surgery, primary care sports medicine, physical therapy, or athletic training were excluded. The remaining 888 participants included 170 orthopaedic surgeons (88% shoulder specialists), 108 primary care sports medicine physicians, 379 physical therapists, and 231 athletic trainers (Table 1).

Orthopaedic surgeons and physical therapists most commonly worked in private practice. Primary care sports medicine physicians most commonly practiced in academic medical centers. Athletic trainers most commonly practiced in "other" settings. "Other" practice settings across all specialties included the treatment of military, athletic (high school, collegiate, and professional), outpatient, and educational (secondary and post-secondary) patient populations.

IMPORTANCE OF CLINICAL FACTORS IN DIAGNOSIS OF SHOULDER INSTABILITY

The importance of clinical factors used to differentiate shoulder instability from rotator cuff impingement differed between physicians and rehabilitation providers (Figure 2). All specialties reported that subluxation is important to the diagnosis of shoulder instability, rating it as their highest or second-highest overall factor (Table 2). However, physicians (orthopaedic surgeons, primary care sports medicine physicians) tended to consider physical examination clinical factors more important to diagnose shoulder instability whereas rehabilitation providers (physical therapists, athletic trainers) valued patient history factors. Both orthopaedic surgeons and primary care sports medicine physicians ranked apprehension tests and relocation tests as their highest and third-highest clinical factors, respectively. Apprehension tests were rated significantly higher by orthopaedic surgeons than by physical therapists and athletic trainers (both P<0.001). Further, relocation tests were rated significantly higher by both physician specialties than by physical therapists and athletic trainers (all P<0.008). In contrast, physical therapists and athletic trainers ranked history of significant trauma and history of repetitive overuse, two patient history factors, among their top three clinical factors used to differentiate shoulder instability from impingement. Both rehabilitation provider specialties rated history of repetitive overuse significantly higher than orthopaedic surgeons (both P<0.001), and rehabilitation providers rated history of significant trauma significantly

---

Table 1

<table>
<thead>
<tr>
<th>Clinical Factor</th>
<th>Orthopaedic Surgeons</th>
<th>Physical Therapists</th>
<th>Athletic Trainers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subluxation</td>
<td>Very Important</td>
<td>Very Important</td>
<td>Very Important</td>
</tr>
<tr>
<td>History of Significant Trauma</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Pain/Limitation in Passive Range of Motion</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Pain/Limitation in Active Range of Motion</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Attraction Tests</td>
<td>Not Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Relocation Tests</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Impingement Tests</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
</tbody>
</table>

---

Figure 1. Summary of survey questions assessing the diagnosis of shoulder instability among physicians and rehabilitation providers.
higher than primary care sports medicine physicians (P=0.005-0.017). The main exception to this trend was age; both physician specialties rated age significantly higher than both rehabilitation provider specialties (P<0.006). No differences were noted between any clinical specialties on the three physical exam tests used to assess glenohumeral joint laxity (load and shift tests, sulcus test, drawer tests); no specialty rated one of these tests any higher than sixth overall (Table 2).

**CLINICAL SCENARIO DIAGNOSIS**

When diagnosing the young athlete in scenario 1, whose physical exam findings included positive apprehension and relocation tests, positive impingement signs, and a negative sulcus sign, most clinicians chose either secondary impingement or unidirectional instability (Figure 3A). The responses from orthopaedic surgeons in scenario 1 differed significantly from all other specialties, leaning towards a diagnosis of secondary impingement (62% vs. 48-54% secondary impingement, 29% vs. 35-42% unidirectional instability; all P<0.001). The distribution of responses in either scenario did not differ between practice settings within any of the clinical specialties (scenario 1: P>0.45; scenario 2: P>0.46). "Other" diagnoses in scenario 1 included alternative rotator cuff pathologies, labral tears, and combinations of impingement and instability. "Other" diagnoses in scenario 2 primarily included combinations of impingement and instability. Participants reported a median of 10-30% and 5-20% of their new patient encounters with shoulder pain presented similarly to scenario 1 and scenario 2, respectively (Figure 3C).
Figure 2. Rated importance of clinical factors to differentially diagnose shoulder instability versus rotator cuff impingement.

Ratings are depicted as a proportion of all responses for a single clinical factor within a specialty. Clinical factors are ordered (1-15) based on unweighted averages across all four specialties. Clinical Specialty: Ortho = Orthopaedic Surgery; PCSM = Primary Care Sports Medicine; PT = Physical Therapy; ATC = Athletic Training.
Table 2. The ranking of clinical factors used to differentiate shoulder instability versus rotator cuff impingement rated in importance by sports medicine physicians and rehabilitation providers.

<table>
<thead>
<tr>
<th>Clinical Factor</th>
<th>Orthopaedic Surgery (N=120&lt;sup&gt;12&lt;/sup&gt;)</th>
<th>Primary Care Sports Medicine (N=108)</th>
<th>Physical Therapy (N=379)</th>
<th>Athletic Training (N=231)</th>
<th>All (N=838&lt;sup&gt;2&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report of Subluxation</td>
<td>2&lt;sup&gt;a,b&lt;/sup&gt; 4.14 ± 0.07</td>
<td>2&lt;sup&gt;b&lt;/sup&gt; 4.00 ± 0.08</td>
<td>1&lt;sup&gt;a&lt;/sup&gt; 4.29 ± 0.04</td>
<td>1&lt;sup&gt;a,b&lt;/sup&gt; 4.23 ± 0.05</td>
<td>1* 4.17 ± 0.06</td>
</tr>
<tr>
<td>Apprehension Tests</td>
<td>1&lt;sup&gt;a&lt;/sup&gt; 4.18 ± 0.06</td>
<td>1&lt;sup&gt;a,b&lt;/sup&gt; 4.03 ± 0.07</td>
<td>4&lt;sup&gt;c&lt;/sup&gt; 3.75 ± 0.05</td>
<td>5&lt;sup&gt;b,c&lt;/sup&gt; 3.79 ± 0.06</td>
<td>2‡ 3.94 ± 0.06</td>
</tr>
<tr>
<td>History of Significant Trauma</td>
<td>5&lt;sup&gt;a,b&lt;/sup&gt; 3.84 ± 0.09</td>
<td>4&lt;sup&gt;b&lt;/sup&gt; 3.74 ± 0.10</td>
<td>2&lt;sup&gt;a&lt;/sup&gt; 4.04 ± 0.05</td>
<td>3&lt;sup&gt;b&lt;/sup&gt; 4.12 ± 0.06</td>
<td>2* 3.94 ± 0.08</td>
</tr>
<tr>
<td>History of Repetitive Overuse</td>
<td>8&lt;sup&gt;c&lt;/sup&gt; 3.34 ± 0.09</td>
<td>5&lt;sup&gt;b,c&lt;/sup&gt; 3.71 ± 0.08</td>
<td>3&lt;sup&gt;b&lt;/sup&gt; 3.91 ± 0.05</td>
<td>2&lt;sup&gt;a&lt;/sup&gt; 4.13 ± 0.05</td>
<td>4‡ 3.77 ± 0.07</td>
</tr>
<tr>
<td>Relocation Tests</td>
<td>3&lt;sup&gt;a&lt;/sup&gt; 3.95 ± 0.08</td>
<td>3&lt;sup&gt;a&lt;/sup&gt; 3.93 ± 0.09</td>
<td>6&lt;sup&gt;b&lt;/sup&gt; 3.57 ± 0.05</td>
<td>12&lt;sup&gt;c&lt;/sup&gt; 3.25 ± 0.04</td>
<td>5‡ 3.67 ± 0.07</td>
</tr>
<tr>
<td>Overhead Athletic Participation</td>
<td>10&lt;sup&gt;c&lt;/sup&gt; 3.18 ± 0.09</td>
<td>9&lt;sup&gt;b,c&lt;/sup&gt; 3.51 ± 0.09</td>
<td>5&lt;sup&gt;b&lt;/sup&gt; 3.69 ± 0.05</td>
<td>4&lt;sup&gt;a&lt;/sup&gt; 4.01 ± 0.06</td>
<td>6‡ 3.60 ± 0.07</td>
</tr>
<tr>
<td>Load and Shift Tests</td>
<td>6&lt;sup&gt;a&lt;/sup&gt; 3.54 ± 0.09</td>
<td>10&lt;sup&gt;a&lt;/sup&gt; 3.39 ± 0.10</td>
<td>11&lt;sup&gt;a&lt;/sup&gt; 3.29 ± 0.05</td>
<td>10&lt;sup&gt;a&lt;/sup&gt; 3.46 ± 0.06</td>
<td>7 3.42 ± 0.08</td>
</tr>
<tr>
<td>Sulcus Sign Tests</td>
<td>7&lt;sup&gt;a&lt;/sup&gt; 3.36 ± 0.08</td>
<td>7&lt;sup&gt;a&lt;/sup&gt; 3.57 ± 0.09</td>
<td>9&lt;sup&gt;a&lt;/sup&gt; 3.33 ± 0.06</td>
<td>11&lt;sup&gt;a&lt;/sup&gt; 3.28 ± 0.07</td>
<td>8 3.38 ± 0.08</td>
</tr>
<tr>
<td>Strength Tests</td>
<td>9&lt;sup&gt;b&lt;/sup&gt; 3.22 ± 0.09</td>
<td>11&lt;sup&gt;b&lt;/sup&gt; 3.22 ± 0.10</td>
<td>8&lt;sup&gt;b&lt;/sup&gt; 3.34 ± 0.05</td>
<td>6&lt;sup&gt;a&lt;/sup&gt; 3.64 ± 0.06</td>
<td>9‡ 3.35 ± 0.08</td>
</tr>
<tr>
<td>Rotator Cuff Impingement Signs</td>
<td>11&lt;sup&gt;b&lt;/sup&gt; 3.08 ± 0.09</td>
<td>6&lt;sup&gt;a&lt;/sup&gt; 3.59 ± 0.10</td>
<td>13&lt;sup&gt;b&lt;/sup&gt; 3.15 ± 0.06</td>
<td>9&lt;sup&gt;a&lt;/sup&gt; 3.58 ± 0.06</td>
<td>10‡ 3.35 ± 0.08</td>
</tr>
<tr>
<td>Age</td>
<td>4&lt;sup&gt;a&lt;/sup&gt; 3.87 ± 0.08</td>
<td>8&lt;sup&gt;a&lt;/sup&gt; 3.52 ± 0.09</td>
<td>12&lt;sup&gt;b&lt;/sup&gt; 3.17 ± 0.05</td>
<td>14&lt;sup&gt;a&lt;/sup&gt; 2.70 ± 0.07</td>
<td>11‡ 3.31 ± 0.07</td>
</tr>
<tr>
<td>Active Range-of-Motion Limitation</td>
<td>13&lt;sup&gt;c&lt;/sup&gt; 2.88 ± 0.09</td>
<td>13&lt;sup&gt;b,c&lt;/sup&gt; 3.06 ± 0.10</td>
<td>7&lt;sup&gt;a&lt;/sup&gt; 3.40 ± 0.05</td>
<td>8&lt;sup&gt;a,b&lt;/sup&gt; 3.59 ± 0.20</td>
<td>12‡ 3.22 ± 0.12</td>
</tr>
<tr>
<td>Passive Range-of-Motion Limitation</td>
<td>14&lt;sup&gt;c&lt;/sup&gt; 2.83 ± 0.09</td>
<td>12&lt;sup&gt;b,c&lt;/sup&gt; 3.07 ± 0.10</td>
<td>10&lt;sup&gt;a&lt;/sup&gt; 3.31 ± 0.05</td>
<td>7&lt;sup&gt;a&lt;/sup&gt; 3.60 ± 0.06</td>
<td>13‡ 3.20 ± 0.08</td>
</tr>
<tr>
<td>Drawer Tests</td>
<td>12&lt;sup&gt;a&lt;/sup&gt; 3.04 ± 0.10</td>
<td>13&lt;sup&gt;a&lt;/sup&gt; 3.06 ± 0.10</td>
<td>14&lt;sup&gt;a&lt;/sup&gt; 3.05 ± 0.05</td>
<td>13&lt;sup&gt;a&lt;/sup&gt; 3.24 ± 0.06</td>
<td>14 3.10 ± 0.08</td>
</tr>
<tr>
<td>Sex</td>
<td>15&lt;sup&gt;b&lt;/sup&gt; 1.88 ± 0.08</td>
<td>15&lt;sup&gt;a&lt;/sup&gt; 2.25 ± 0.09</td>
<td>15&lt;sup&gt;a&lt;/sup&gt; 2.26 ± 0.05</td>
<td>15&lt;sup&gt;b&lt;/sup&gt; 1.83 ± 0.06</td>
<td>15‡ 2.06 ± 0.07</td>
</tr>
</tbody>
</table>

Physical examination clinical factors are shaded in gray and patient history clinical factors are unshaded. Group differences within a clinical factor between specialties: *P<0.05/15; ‡P<0.01/15. <sup>a</sup>-<sup>c</sup> Specialty means (means ± standard error based on 5-point Likert scale) that do not share the same superscript letter in each row differ at P<0.05. Bold numbers indicate the rank of each clinical factor within each clinical specialty. Means in the All column are unweighted averages of all four specialties. <sup>12</sup> Of 170 Ortho completed the clinical factor portion of the survey. <sup>2</sup> Of 231 ATC rated the importance of active range-of-motion limitation.
DISCUSSION

The goal of this study was to explore potential differences in clinical perspectives among physicians and rehabilitation providers in criteria used to diagnose shoulder instability. We accomplished this goal by surveying clinicians about the importance of common clinical factors to diagnosing shoulder instability and differentiating it from rotator cuff impingement. Overall, physicians differed from rehabilitation providers in how they rated the importance of these clinical factors, confirming our primary hypothesis. Physicians preferred physical examination factors, whereas rehabilitation providers instead preferred patient history factors as discussed in further detail below. Additionally, we surveyed sports medicine clinicians about the diagnosis they would choose for clinical scenarios with concurrent clinical findings of atraumatic shoulder instability and rotator cuff impingement. The results of this study indicate in this particular patient scenario that clinicians were split in diagnosing patients with secondary impingement or unidirectional instability when positive impingement signs, a positive apprehension test, and a negative sulcus sign were present. These differences in diagnostic labels can be confusing to the athlete seeking care, and they ultimately may delay the effectiveness of patient recovery. With the addition of a positive sulcus sign to an otherwise identical clinical scenario, the majority of clinicians chose a diagnosis of multidirectional instability. This finding demonstrates the universal importance of the sulcus sign in the diagnosis of multidirectional instability. Orthopaedic surgeons differed from other specialties in both scenarios, preferring impingement-focused instead of instability-focused diagnostic labels.

DIFFERENCES IN RATINGS OF CLINICAL FACTORS USED TO DIFFERENTIATE SHOULDER INSTABILITY FROM IMPINGEMENT

The tendency of orthopaedic surgeons and primary care sports medicine physicians to rate the apprehension and relocation tests as two of the most important factors suggests both specialties recognize the high specificity of these tests to rule in shoulder instability.26 When both positive, the apprehension and relocation tests have high sensitivity (81%) and specificity (98%) in diagnosing anterior shoulder instability.27 Physical therapists and athletic trainers rated the apprehension test among their top five factors as well, yet athletic trainers rated the relocation test noticeably lower than all other specialties. While over 55% of orthopaedic surgeons, primary care sports medicine physicians, and physical therapists rated the relocation as "Very Important" or "Crucial" to making their diagnosis, only 23% of athletic trainers answered similarly. Additional education may be warranted across disciplines on the value of the relocation test when used in combination with the apprehension test to diagnose shoulder instability.

As part of their role on sports medicine team, team physician responsibilities include many components that require managing patients during a snapshot of their athletic participation; examples include pre-participation evaluations, patient visits to the clinic after injury, and the management of injuries on the field.28 Given the importance of physical examinations tests to evaluate athletes during individual encounters, this pattern of care may explain their bias towards prioritizing physical examination tests over patient history factors in the differentiation of shoulder instability versus impingement. Interestingly, the responses from primary care sports medicine physicians were very similar to the responses from orthopaedic surgeons despite the former specialty containing multiple subcategories of physicians that manage patients which fall within different demographic groups. On the contrary, the role of rehabilitation providers within the sports medicine team corresponds to more longitudinal interactions with the athletes they are tasked with treating. Athletic trainers specifically interact with an athlete in many circumstances before an injury may occur, such as establishing procedures for safe strengthening, conditioning, and practicing.19 Athletic trainers spend a substantial amount of time with the athlete, which may explain why they rated two patient history factors, history of repetitive overuse and overhead athletic participation, higher than any other specialty. Following an injury, physical therapists are likewise tasked with spending considerable time working directly with athletes throughout their rehabilitation and guiding their return to sport.29 In turn, they also may be more attune to anecdotal relationships between the clinical history of the athlete and

Figure 3. Diagnostic labels for two athlete scenarios with concurrent clinical examination findings of atraumatic shoulder instability and rotator cuff impingement.

A-B) Scenarios 1 and 2 only differ by the presence of a negative or positive sulcus sign, respectively. C) Percentage of new encounters with shoulder pain with signs and symptoms consistent with each athlete scenario who present to each specialty (median [interquartile range]); Differences in the distributions of scenario diagnoses between specialties: *P<0.001; **P<0.001. Clinical Specialty: Ortho = Orthopaedic Surgery; PCSM = Primary Care Sports Medicine; PT = Physical Therapy; ATC = Athletic Training.
the development of symptoms, which may affect their preference towards rating patient history factors so highly.

THE SULCUS SIGN AND THE DIAGNOSIS OF ATRAUMATIC MULTIDIRECTIONAL INSTABILITY

Our results highlight the importance clinicians place on the sulcus sign when diagnosing atraumatic instability despite the debate over its utility as a marker of inferior laxity versus a diagnostic tool for shoulder instability.\(^9,43\) The addition of a positive sulcus sign to scenario 2, which was otherwise identical to scenario 1, prompted a large shift in diagnoses among all specialties from unidirectional instability and secondary impingement to multidirectional instability. These results align with a common classification of shoulder instability, which suggests multidirectional instability is present with a positive sulcus sign coupled with a positive provocative test for anterior or posterior instability (e.g., apprehension test).\(^9\) Further, clinicians reported using the sulcus sign to differentiate between multidirectional instability and unidirectional instability or secondary impingement despite placing less importance on the sulcus sign to differentiate between instability and impingement compared to other clinical factors.

Authors of previous studies, which have highlighted discrepancies in the diagnosis of atraumatic shoulder instability, expressed concern over the use of the sulcus sign when evaluating for shoulder instability; they suggested only associating a positive sulcus sign with inferior instability if symptoms are present with inferior laxity.\(^30\) Commonly, clinical laxity tests used to assess excessive glenohumeral translation are positive regardless of whether symptoms of pain or apprehension are provoked.\(^32\) Unfortunately, no specific provocative tests for inferior instability have since been designed for use in clinical practice, likely due to the low incidence of isolated inferior instability among athletes\(^35\) and the general population.\(^34\) Apprehension tests are instead only equipped to probe for symptoms of instability in the anterior and posterior directions. Indeed, certain studies including patients with multidirectional instability do describe symptomatic inferior laxity as part of their inclusion criteria, but they fail to attribute inferior symptoms to any physical examination technique.\(^12,35\) Observing the reproduction of instability symptoms in addition to excessive translation when grading tests for inferior instability has been advocated,\(^30,36\) given the value assigned to provocative tests when diagnosing shoulder instability.\(^9\)

CLINICAL IMPLICATIONS

Consistency in the diagnosis of shoulder instability is critical to optimal interdisciplinary care of the athlete. The development of clinical guidelines for the diagnosis and treatment of shoulder instability may help increase consistency among all sports medicine clinicians. These guidelines should be organized by an interdisciplinary team of sports medicine clinicians, as have been developed for shoulder pathologies such as rotator cuff injuries and glenohumeral osteoarthritis.\(^37,38\) Such guidelines should build on current patient care pathways for atraumatic shoulder instability\(^39,40\) and clarify the collective importance of different physical examination and patient history factors towards making a diagnosis of athletes’ shoulder pain. Clarifying the role of the sulcus sign in the assessment of atraumatic shoulder instability may also be warranted, given the large influence the sulcus sign plays among all sports medicine clinicians in the diagnosis of multidirectional instability. Additionally, interdisciplinary sports medicine conferences may help overcome differences in the education of musculoskeletal medicine recognized among different specialties and improve consistency in diagnostic language.\(^41–45\) Similar recommendations of collaboration have been advocated based on differences in opinion among orthopaedic surgeons and physical therapists in the role of rehabilitation following rotator cuff repair.\(^44\)

LIMITATIONS

The use of a survey instrument is associated with both volunteer and recollection biases. However, the distribution of a survey via email to multiple professional clinical societies allowed for acquisition of responses from a large cohort practicing in sports medicine that would otherwise be unattainable. Additional clinical factors potentially considered in the diagnosis of shoulder instability\(^9,43,46\) were not included in this study’s rating of clinical factors and could have provided further insight into how clinicians diagnose the condition. Finally, the two scenarios used in this study were brief, not including all information that clinicians may have access to when assessing a patient. The two scenarios also included more physical examination findings than patient history factors, potentially limiting how rehabilitation providers could evaluate the scenario given the emphasis they placed on patient history factors to differentiate shoulder instability from rotator cuff impingement. Additional clinical, radiographic, and demographic information was withheld to avoid creating a scenario too specific to generalize to broader cases of atraumatic shoulder instability.

CONCLUSION

Sports medicine clinicians differed between specialties in the clinical factors believed to be important to diagnose shoulder instability in athletes. Furthermore, agreement on the diagnostic labels used with athletes that present with clinical findings of atraumatic shoulder instability is lacking. More consensus is warranted to improve the consistency of clinical factors used to diagnose shoulder instability and differentiate this from concurrent rotator cuff impingement findings. Shoulder instability clinical practice guidelines, consensus meetings, and interdisciplinary educational opportunities are needed to optimize care for athletes commonly treated by a variety of sports medicine specialties.

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CONFLICTS OF INTEREST

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1R01HD098698-01, AHQR 1R01HS027426-01, NCATS
UL1TR001422) outside of the submitted work. ALS also
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Shoulder and Elbow Therapists, on the Editorial Board for
the Journal Orthopaedic and Sports Physical Therapy, and
as Vice Chair of the Research Committee for the Academy of
Orthopaedic Physical Therapy. XL reports consultant fees,
royalties, I.P., and non-financial support from FH Ortho and
consultant fees from Mitek-Depuy outside of the submitted
work. XL also serves on the Editorial Board for the American
Journal Sports Medicine, on the Editorial Board for Orth-
opedics Review, on the Research Committee for the American
Society Shoulder and Elbow Surgeons, and as Sports Medi-
cine and Arthroscopy ICL Chair for the American Academy
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CDT
REFERENCES


Background
Shoulder strength deficits are implicated in arm injuries and performance deficits in baseball players.

Purpose
To characterize shoulder external (ER) and internal (IR) rotation strength in professional baseball players, and compare strength across player type (pitchers, position players) and geographic origin (North America, Latin America).

Study Design
Cross-sectional.

Methods
Minor league professional baseball players from North America and Latin America (n=424; age=22.4±2.3 years; n=135 pitchers and n=107 position players; n=162 North American and n=80 Latin American players) volunteered at spring training. Bilateral shoulder IR and ER isometric strength was measured in sitting with the arm at the side using a handheld dynamometer stabilized on a wall via a specialized jig. Strength was normalized to body weight, and compared using t-tests between player type and geographic area of origin (p < 0.05).

Results
Position players had greater strength in ER, IR and ER:IR (ER:0.7-2.7N/kg; IR:1.3-3.8N/kg; ER:IR ratio 0.36-1.22) compared to pitchers (ER:0.5-2.5N/kg; IR:0.6-4.2N/kg; ER:IR ratio 0.44-1.16) on the throwing arm. North American pitchers had lower ER [MD= -0.4 (95%CI:-0.7,-0.2);p=0.002] and IR [MD= -0.2 (95%CI:-0.4,-0.1);p=0.006] than Latin American pitchers on the throwing arm. There were no differences between geographic groups for position players.

Discussion/Conclusions
Player position and geographic origin influence shoulder rotational strength values in professional baseball players. Position players have 14 – 20% higher ER and IR isometric strength.
strength than pitchers. Moreover, Latin American pitchers exhibited 11.8% greater ER strength and 16.7% greater IR strength as compared to North American pitchers. Normative values can be used to determine player deficits, declines in performance, and targets for return to play after injury.

**Level of Evidence**

Level II

**INTRODUCTION**

Baseball continues to be a popular sport played worldwide. Upper extremity injuries are prevalent, accounting for more than 54% of all days spent on the disabled list for professional baseball players.\(^1\) Injury risk is related to the position played, with pitchers reporting the highest number of upper extremity injuries.\(^1,2\) Shoulder girdle muscles provide stabilization and control of the glenohumeral joint during acceleration, deceleration, and follow through phases of throwing. Specific deficits in strength of the muscles of shoulder external rotation (ER) and internal rotation (IR), and the ER:IR ratio have been linked to upper extremity injury\(^5,4\) and impact on performance\(^5\) in baseball. Normative data on shoulder rotational strength profiles are needed to identify deficits, and enable return to sport decision-making.

The majority of baseball-related literature has focused on pitchers.\(^6\) Given the variability in throwing mechanics and demands between position players and pitchers, rotational shoulder strength profiles may be different. Studies are limited that describe shoulder ER and IR strength in non-injured professional baseball pitchers and position players using isokinetic and isometric methods.\(^4,7–9\) Unfortunately, isokinetic equipment is expensive, and not readily available for all baseball organizations.\(^7,9\) Hand held dynamometers (HHD) are less expensive, clinically available, and are easy to use to test strength. Prior studies using a HHD have not consistently provided adequate stabilization, contributing to high variability in the strength measures.\(^4,8\)

Normative strength profiles may also be impacted by demographic and cultural factors. Approximately 40% of professional baseball players are born outside of the United States.\(^10,11\) Practice frequency and duration,\(^6,12\) season and offseason length,\(^13\) strength and conditioning practices, and health services practices vary between geographic regions. Two prior studies found that baseball players from the Latin America had greater humeral retroversion and different functional shoulder movement patterns than those from the United States.\(^14,15\) Cultural factors of a geographic region may define the parameters of sport training, and thus influence performance, movement, and strength patterns.

Currently, it is unclear if shoulder rotational strength profiles are influenced by position played and geographic region of origin. The purpose of this study was to describe shoulder ER, IR, and ER:IR strength values in Minor League Baseball (MiLB) professional players, and to compare strength values across geographic origin (North American versus Latin American) players and between player type (pitcher versus position player).

**METHODS**

A cohort study design was used to characterize the shoulder rotational strength profiles for professional MiLB baseball players. Player type categorized players as position player or pitcher to determine the differences of player type on strength. Players who listed pitching as a secondary position, were classified as a pitcher if they pitched at least 10, multiple-inning games in the previous season. Geographic area of origin was defined by two groups; North America and Latin America. The North American group consisted of athletes from the United States and Canada. The Latin American group consisted of athletes from the Dominican Republic, Puerto Rico, Venezuela, Colombia, Cuba, Mexico, and Panama.

**SUBJECTS**

Data were collected on 242 professional MiLB baseball players (n=135 pitchers and n=107 position players) during each year of three years of spring training physical examinations (2016–2018). If a player was tested more than once over the three years, only the most recent year was used for data analysis. Inclusion criteria was: on a team roster for a MiLB team at pre-season. Exclusion criteria were 1) not cleared to participate in baseball activities, 2) current report of pain in the shoulder or elbow, 3) currently receiving treatment for a shoulder or elbow injury, and 4) from a country outside of Latin and North Americas. Demographics grouped by position and geographic region are described in Table 1. Years of MiLB experience was defined as the number of years from the year drafted. This study was approved by the Institutional Review Board (IRB) at the University of Southern California, and the subjects signed an informed consent to participate in this study.

**PROCEDURES**

Height and weight were measured using a tape measure and scale respectively. Shoulder strength was measured on both their dominant and non-dominant arms. Shoulder ER and IR strength were measured in a seated position, with the arm placed by the side with a towel roll under the axilla, and the elbow flexed to 90° (Figure 1). A handheld dynamometer (Hoggan Scientific, Lafayette, IN) was attached to a stabilizing device that was novel for this investigation (see Figure 1) and aligned for placement on the posterior forearm just proximal to the ulnar styloid for ER strength. For IR strength, the handheld dynamometer was placed on the anterior forearm just proximal to the wrist. Players performed two maximal effort isometric contractions with the instructions to "push as hard as possible for five seconds". One minute of rest was given between each trial. Strength
values were normalized to body weight (N/kg). The average of two trials for shoulder ER and IR, and ER to IR ratio (ER/IR) was used for data analysis.
<table>
<thead>
<tr>
<th>Group Size</th>
<th>N</th>
<th>Mean ± SD</th>
<th>25th, 75th</th>
<th>Mean ± SD</th>
<th>25th, 75th</th>
<th>Mean ± SD</th>
<th>25th, 75th</th>
<th>Mean ± SD</th>
<th>25th, 75th</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Athletes</td>
<td>All Players</td>
<td>242</td>
<td>22.4 ± 2.3</td>
<td>21.0, 24.0</td>
<td>185.9 ± 6.7</td>
<td>182.9, 190.5</td>
<td>89.8 ± 11.0</td>
<td>81.8, 97.9</td>
<td>2.7 ± 1.8</td>
</tr>
<tr>
<td></td>
<td>Pitchers</td>
<td>135</td>
<td>22.6 ± 2.4</td>
<td>21.0, 24.0</td>
<td>188.6 ± 6.3a</td>
<td>182.9, 193.0</td>
<td>92.4 ± 11.2a</td>
<td>84.1, 100.0</td>
<td>2.7 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>Position Players</td>
<td>107</td>
<td>22.2 ± 2.2</td>
<td>21.0, 24.0</td>
<td>182.4 ± 5.4a</td>
<td>177.8, 185.4</td>
<td>86.5 ± 9.9a</td>
<td>79.5, 92.7</td>
<td>2.7 ± 1.8</td>
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<tr>
<td>North America</td>
<td>All Players</td>
<td>162</td>
<td>23.3 ± 1.9c</td>
<td>22.0, 24.0</td>
<td>186.9 ± 6.7c</td>
<td>182.9, 190.5</td>
<td>92.6 ± 9.2c</td>
<td>86.4, 96.4</td>
<td>2.3 ± 1.7c</td>
</tr>
<tr>
<td></td>
<td>Pitchers</td>
<td>101</td>
<td>23.4 ± 1.9b</td>
<td>23.0, 24.0</td>
<td>189.3 ± 6.4bd</td>
<td>185.4, 193.0</td>
<td>94.6 ± 9.5bd</td>
<td>88.6, 100.7</td>
<td>2.5 ± 1.8bd</td>
</tr>
<tr>
<td></td>
<td>Position Players</td>
<td>61</td>
<td>23.0 ± 1.8b</td>
<td>22.0, 24.0</td>
<td>183.0 ± 5.4d</td>
<td>180.3, 185.4</td>
<td>89.1 ± 7.7bd</td>
<td>84.1, 94.3</td>
<td>1.9 ± 1.2bd</td>
</tr>
<tr>
<td>Latin America</td>
<td>All Players</td>
<td>80</td>
<td>20.8 ± 2.3c</td>
<td>19.0, 23.0</td>
<td>183.7 ± 6.0c</td>
<td>180.3, 188.0</td>
<td>84.2 ± 12.3c</td>
<td>76.4, 90.5</td>
<td>3.6 ± 1.9c</td>
</tr>
<tr>
<td></td>
<td>Pitchers</td>
<td>34</td>
<td>20.2 ± 2.3b</td>
<td>19.0, 21.3</td>
<td>186.8 ± 5.6bd</td>
<td>182.9, 191.1</td>
<td>85.8 ± 13.4b</td>
<td>76.4, 91.7</td>
<td>3.4 ± 2.0b</td>
</tr>
<tr>
<td></td>
<td>Position Players</td>
<td>46</td>
<td>21.2 ± 2.2b</td>
<td>20.0, 23.0</td>
<td>181.4 ± 5.4d</td>
<td>177.8, 185.4</td>
<td>83.0 ± 11.5b</td>
<td>75.0, 89.8</td>
<td>3.7 ± 1.8b</td>
</tr>
</tbody>
</table>

MiLB = Minor League Baseball

a = Significant differences between pitcher vs. position player, collapsed by geographic areas of origin; $\alpha = 0.05$

b = Significant differences between Latin America vs. North America for pitchers; $\alpha = 0.05$

c = Significant differences between Latin America vs. North America, collapsed by athlete player type; $\alpha = 0.05$

d = Significant differences between pitcher vs. position player, within a geographic area of origin; $\alpha = 0.05$
Test-retest reliability for shoulder isometric strength measurements was established prior to data collection. Interclass correlation coefficient (ICC) 2-way mixed model, standard error of the measure (SEM), and minimal detectable change \[ \text{MDC90\%} = \text{SEM} \times \sqrt{2} \] were calculated on \( n=10 \) subjects prior to athlete testing. For IR strength, the ICC (3,2) was 0.96; error metrics of the SEM of 0.09N/kg and the MDC90\% of 0.20N/kg. For ER strength, the ICC (3,2) was 0.95; error metrics of the SEM of 0.08N/kg and the MDC90\% of 0.18N/kg. For ER:IR, the ICC (3,2) was 0.97, error metrics of the SEM of 0.05N/kg and for the MDC90\% of 0.11N/kg.

Sample size calculations were based on the MDC for ER, IR, and ER:IR; 80\% power and a significance level of 0.05 indicated the largest sample size of 90 athletes, with 45 per group for comparisons.

**STATISTICAL ANALYSES**

Shoulder strength mean and variance values were calculated for both the throwing and non-throwing arms. To determine if strength profiles of players from Latin American countries could be considered a homogenous group, a sensitivity analysis was performed on players from the Dominican Republic (\( n = 40 \)), Venezuela (\( n = 26 \)), Puerto Rico (\( n = 7 \)), Mexico (\( n = 2 \)), Panama (\( n = 2 \)), Cuba (\( n = 2 \)), Colombia (\( n = 1 \)). An ANOVA was performed between the groups with sufficient sample sizes (Dominican Republic and Venezuela), resulting in no differences in ER or IR strength values. For the five remaining countries with one to seven players, data was plotted by country. All values from these five countries were within the range for the group formed by the Dominican Republic and Venezuela, except for one Cuban player. For this Cuban player only the ER:IR on the non-dominant arm fell outside the range, but the measured ER and IR values for both arms were within the range of the larger group, so this player was included in the final data set. Data from the seven Latin American countries were considered a single, homogenous group for analysis.

Independent samples t-tests with equal variance were performed to identify differences in descriptive statistics (age, height, weight, age drafted, MiLB experience) between and within samples (pitcher vs. position player, North American vs. Latin American). Independent t-tests with equal variances were also used to test for differences in strength measures between Latin American and North American athletes (all athletes and comparisons of position players and pitchers), and between pitchers and position players (grouped by geographic area of origin and throwing arm). Statistical analyses were performed using IBM SPSS Statistics Version 24.0 (IBM, Armonk, NY) and R software (The R Foundation), alpha level of \( p \leq 0.05 \).

**RESULTS**

**NORMATIVE DATA**

Table 1 presents the age, height, weight, and years of MiLB experience of the participants.

Normative data for athletes grouped by position and geographic area of origin are depicted in Figures 2 and 3. Pitchers throwing arm strength ranged for IR of 0.6 to 4.2 N/kg, ER of 0.5 to 2.5 N/kg, and an ER:IR ratio of 0.44 to 1.16. Pitchers’ non-throwing arm had strength ranges for IR of 0.6 to 3.7 N/kg, ER of 0.7 to 2.9 N/kg, and an ER:IR ratio ranging from 0.38 to 1.31. Position players throwing arm strength range for IR of 1.3 to 3.8 N/kg, ER 0.7 to 2.7 N/kg, and ER:IR ratio range of 0.36 to 1.22. For the non-throwing arm, position players strength for IR ranged from 1.1 to 4.1 N/kg, ER of 1.0 to 2.8 N/kg, and ER:IR of 0.47 to 1.44.

**NORTH AMERICAN VERSUS LATIN AMERICAN PLAYERS**

Strength profiles by geographic region (Table 2) indicated Latin American athletes were stronger in ER and IR on the non-throwing and throwing arms \((p=0.005\text{ to }<0.001)\), collapsed across player type than North American athletes. There were no differences between geographic regions on ER:IR ratios on the throwing arm \((p=0.898)\) and non-throwing arm \((p=0.824)\).

**PITCHERS VERSUS POSITION PLAYERS**

Strength profiles by player type (Table 3) indicated that pitchers were weaker in IR, ER, and ER:IR ratio when compared to position players for both the non-throwing arm and non-throwing arm \((p=0.0433\text{ to }<0.001)\), collapsed across geographic regions.
PLAYER TYPE BY POSITION AND GEOGRAPHIC REGION INTERACTION

In North American players (Table 3), position players have higher ER and IR strength as compared to pitchers, for both the throwing arm (p < 0.001) and non-throwing arm (p <0.001, p=0.002 respectively). There were no differences between North American position players and pitchers in ER:IR strength ratio for the throwing (p=0.358) and non-throwing (p=0.102) arms.

Among Latin American athletes (Table 3), the ER:IR ratio was higher on the throwing arm in the position players versus pitchers (p=0.020). Additionally, position players were stronger in ER (p=0.002) and IR (p=0.037) on the non-throwing arm as compared to pitchers from Latin America. There were no significant differences (p=0.119) between Latin American position players and pitchers in ER:IR strength ratio for the non-throwing arm.

Differences between geographic region by position indicate that North American pitchers were weaker in ER [MD= -0.4 (95%CI: -0.7, -0.2), p=0.002] and IR [MD= -0.2 (95%CI: -0.4, -0.1), p=0.006] for the throwing arm when compared to their Latin American counterparts; all other strength measures were not different between geographic groups for pitchers. For position players, there were no differences between geographic groups.

DISCUSSION

Shoulder ER and IR muscles have a central role in glenohumeral stabilization, as well as arm acceleration and deceleration throughout the throwing motion. Shoulder ER and IR strength varied across player type and geographic region of origin in a cohort of 242 professional baseball players. Generally, position players were stronger than pitchers, and Latin American players tended to be stronger than their North American counterparts. Position players had higher ER and IR isometric strength than pitchers, respectively by 14 – 20% on their throwing arm and 15 – 20% on the non-throwing arm. Thus, the ER:IR ratio was higher by 5.5% and 6.9% on throwing and non-throwing arm respectively. Latin American players across both arms had 9.5 – 14.5% higher isometric strength over North American players. Considering the intersection of player position and geographic region, Latin American pitchers exhibited 11.8% greater ER strength and 16.7% greater IR strength as compared to North American pitchers. In the North American region only, position players were stronger in shoulder IR and ER and had a higher ER:IR ratio than pitchers. In Latin American player’s throwing arm, only the ER:IR ratio was different between player type. In the non-throwing arm in Latin American position players had greater shoulder strength than pitchers.

Pitchers were generally weaker than position players. Specifically, position players were stronger in both the throwing and non-throwing arm ER, IR, and ER:IR ratio compared to pitchers.

This was a surprising result. A prior study did find no differences between player type for ER and IR strength, however they used isokinetic testing methods which differed from this current study. Pitchers commonly engage in highly programmed specialized training, often termed “arm care”. The current study may indicate the arm care may be inadequate. Baseball players face different demands related to position, which may influence shoulder strength. Position players play every day whereas pitchers play once every four to five days. Alternatively, higher ball velocity and shoulder loads in pitchers may lead to fatigue or overuse, and thus weaker ER and IR muscles in the throwing arm in comparison to the position player cohort. Finally, player position may be dictated by shoulder strength; e.g., players who are stronger may select into a position player versus pitcher. These results may imply a change is needed in the training program for pitchers, with a focus on ER and IR strengthening.

Normative strength data derived from healthy players provide metrics that may be used to identify deficits that may be associated with injury or poor performance. For the throwing arm, pitchers had a mean range for IR strength of 0.6 to 4.2 N/kg and ER of 0.5 to 2.5 N/kg, while position

Figure 2. Individual player strength profiles for external rotation (ER), internal rotation (IR), and ER:IR shoulder strength by player type.

Figure 3. Individual player strength profiles for external rotation (ER), internal rotation (IR), and ER:IR shoulder strength by geographic region player type.
players IR strength ranged from 1.3 to 3.8 N/kg and ER strength from 0.7 to 2.7 N/kg. Normalizing strength measures to body weight has a potential influence, as pitchers were heavier than position players. Previous studies in baseball players have assessed strength with the shoulder abducted at 0° or 90°. Assessing strength at 90° is a more functional position that replicates the position of the shoulder during throwing, but may yield different strength values than those at 0° of abduction. Donatelli et al. reported values for HHID isometric ER:IR strength ratio at 90° abduction of 0.83 for the throwing arm and 0.99 in the non-throwing arm in professional baseball players. In the current study, pitchers had a 0.73 ratio for both arms. Position players had a higher ratios (0.77–0.78) in both arms.

A stable throwing shoulder is theorized to have an ER:IR of 1. An ER:IR less than 1 may contribute to upper extremity injury risk in professional baseball players, however examining the ratio alone does not provide direct information if the altered ratio is related to an ER or IR strength deficit. Deficits in ER and IR strength were reported in baseball players who have sustained an ulnar collateral ligament (UCL) injury. Calculating the ER:IR based on the reported means, the ER:IR for healthy pitchers was 0.70 and those with a UCL injury was lower at 0.66. Tennis players with shoulder pain also have a lower ER:IR of 0.68 as compared to healthy players who had a ratio of 0.79. An ER:IR ratio of 0.70 may be the threshold for an injury protective effect. This study presented an average value of 0.75. Future research is needed to define specific ER:IR ratio thresholds for injury risk predictions.

Cultural differences in youth training methods may impact shoulder strength between regions between North American and Latin American players. Latin American athletes were stronger in ER and IR strength on both arms. North American players were heavier, which could be a factor as strength was normalized to body weight. The difference in IR and ER strength between groups exceeded the measurement error of the utilized measure (MDC90%). There are major differences in access to training and coaching between geographical regions with sport performance centers readily available in North America. Regardless of differences in ER and IR strength between countries of origin, all players maintained a similar level of balance in ER:IR strength. Height was not used to normalize strength. A prior study indicated normalization by weight is the most effective method to reduce unwanted variability in shoulder strength measures. However, body weight alone does not account for differences in weight distribution or lean body mass.

It is common for Latin American players to join baseball academies affiliated with Major League Baseball Organizations at the age of 16. Baseball training at that time for Latin American players focuses on skill development and sports specific strengthening, which is likely less than the regimen for their North American counterparts at the same age. Over the years, cultural changes in North America youth baseball have occurred and include year-round baseball, sports specialization, and showcases which increase playing intensity and volume. North American players were older in this study, but had slightly less professional baseball experience than Latin American players. North American players can be drafted immediately following high school or they can wait to play professional baseball three years after high school whereas many Latin American players begin their professional careers after high school or as early as 16 years of age. Participation in the off-season arm care, or playing intensity prior to spring training was not considered. Financial compensation and competitive pressure inside the milieu of professional baseball may have encouraged greater frequency and effort in training. These factors may account for the differences in observed strength.

The use of a standardized strength testing protocol with a stabilized HHID afforded low measurement error and reduced variability. Regarding limitations, information on the cultural upbringing, training access, and training regimens performed by players in this study was not available. Further research documenting training programs, training access and nutritional practices will strengthen the understanding of how exercise affects shoulder strength. All
position players were collapsed into a single group, as there were not enough subjects to do a subgroup analysis for each player type. It is possible that certain position players have different strength profiles due to the specific demands of each position.

**CONCLUSIONS**

Baseball continues to draw a high level of international participation, yet arm injuries remain common. The results of the current study indicate that player position and geographic region of origin have an impact on shoulder rotational strength values in professional baseball players. Position players from both regions have higher shoulder rotational strength values than pitchers. Moreover, Latin American pitchers have stronger ER and IR as compared to their North American counterparts. Normative values of shoulder rotational strength for Latin and North American baseball players can be leveraged to identify player deficits, development of performance training programs, and inform assessment of player performance.

**DISCLOSURE OF FUNDING**

Major League Baseball Research Grant: Risk Factors Associated with Upper Extremity Injuries in Baseball.

**CONFLICTS OF INTEREST**

The authors report no conflicts of interest associated with this manuscript.

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**Table 3. External rotation (ER) and internal rotation (IR) shoulder strength by geographic region and player type mean, standard deviation (SD), and interquartile range; and mean differences (MD) for comparisons.**

<table>
<thead>
<tr>
<th></th>
<th>Position Players Mean ± SD</th>
<th>Position Players 25%, 75%</th>
<th>Pitchers Mean ± SD</th>
<th>Pitchers 25%, 75%</th>
<th>Pitcher vs Position Player MD (95% CI)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Athletes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throwing Arm</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>IR Strength (N/kg)</td>
<td>2.4 ± 0.6</td>
<td>1.9, 2.8</td>
<td>2.1 ± 0.6</td>
<td>1.7, 2.4</td>
<td>0.3 (0.1, 0.4)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER Strength (N/kg)</td>
<td>1.8 ± 0.4</td>
<td>1.5, 2.1</td>
<td>1.5 ± 0.4</td>
<td>1.2, 1.7</td>
<td>0.3 (0.2, 0.4)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER:IR Ratio</td>
<td>0.77 ± 0.17</td>
<td>0.67, 0.88</td>
<td>0.73 ± 0.14</td>
<td>0.64, 0.82</td>
<td>0.04 (0.00, 0.08)</td>
<td>0.043*</td>
</tr>
<tr>
<td>Non-Throwing Arm</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>IR Strength (N/kg)</td>
<td>2.3 ± 0.5</td>
<td>2.0, 2.7</td>
<td>2.0 ± 0.5</td>
<td>1.7, 2.3</td>
<td>0.3 (0.2, 0.4)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER Strength (N/kg)</td>
<td>1.8 ± 0.4</td>
<td>1.5, 2.0</td>
<td>1.5 ± 0.3</td>
<td>1.2, 1.7</td>
<td>0.3 (0.2, 0.4)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER:IR Ratio</td>
<td>0.78 ± 0.18</td>
<td>0.66, 0.86</td>
<td>0.73 ± 0.15</td>
<td>0.61, 0.84</td>
<td>0.05 (0.00, 0.09)</td>
<td>0.033*</td>
</tr>
<tr>
<td><strong>North America</strong></td>
<td></td>
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<tr>
<td>Throwing Arm</td>
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<td></td>
</tr>
<tr>
<td>IR Strength (N/kg)</td>
<td>2.4 ± 0.5</td>
<td>2.0, 2.6</td>
<td>2.0 ± 0.5</td>
<td>1.7, 2.3</td>
<td>0.4 (0.2, 0.5)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER Strength (N/kg)</td>
<td>1.8 ± 0.4</td>
<td>1.5, 2.0</td>
<td>1.5 ± 0.3</td>
<td>1.2, 1.7</td>
<td>0.3 (0.2, 0.4)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER:IR Ratio</td>
<td>0.76 ± 0.16</td>
<td>0.66, 0.87</td>
<td>0.74 ± 0.14</td>
<td>0.66, 0.83</td>
<td>0.02 (-0.03, 0.07)</td>
<td>0.358</td>
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<td>Non-Throwing Arm</td>
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<tr>
<td>IR Strength (N/kg)</td>
<td>2.3 ± 0.5</td>
<td>1.9, 2.7</td>
<td>2.0 ± 0.5</td>
<td>1.6, 2.3</td>
<td>0.3 (0.1, 0.4)</td>
<td>0.002*</td>
</tr>
<tr>
<td>ER Strength (N/kg)</td>
<td>1.7 ± 0.4</td>
<td>1.4, 2.0</td>
<td>1.4 ± 0.3</td>
<td>1.2, 1.6</td>
<td>0.3 (0.2, 0.4)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>ER:IR Ratio</td>
<td>0.78 ± 0.18</td>
<td>0.68, 0.87</td>
<td>0.74 ± 0.16</td>
<td>0.61, 0.84</td>
<td>0.04 (-0.01, 0.10)</td>
<td>0.102</td>
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<tr>
<td><strong>Latin America</strong></td>
<td></td>
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<tr>
<td>Throwing Arm</td>
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</tr>
<tr>
<td>IR Strength (N/kg)</td>
<td>2.4 ± 0.6</td>
<td>1.9, 2.9</td>
<td>2.4 ± 0.7</td>
<td>2.0, 2.7</td>
<td>0.0 (-0.3, 0.3)</td>
<td>0.855</td>
</tr>
<tr>
<td>ER Strength (N/kg)</td>
<td>1.8 ± 0.4</td>
<td>1.5, 2.1</td>
<td>1.7 ± 0.4</td>
<td>1.4, 1.9</td>
<td>0.1 (0.0 - 0.3)</td>
<td>0.058</td>
</tr>
<tr>
<td>ER:IR Ratio</td>
<td>0.78 ± 0.18</td>
<td>0.69, 0.90</td>
<td>0.70 ± 0.12</td>
<td>0.61, 0.77</td>
<td>0.08 (0.01, 0.14)</td>
<td>0.020*</td>
</tr>
<tr>
<td>Non-Throwing Arm</td>
<td></td>
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<td>IR Strength (N/kg)</td>
<td>2.4 ± 0.5</td>
<td>2.0, 2.8</td>
<td>2.2 ± 0.5</td>
<td>1.8, 2.4</td>
<td>0.2 (0.0, 0.5)</td>
<td>0.037*</td>
</tr>
<tr>
<td>ER Strength (N/kg)</td>
<td>1.8 ± 0.4</td>
<td>1.5, 2.1</td>
<td>1.5 ± 0.4</td>
<td>1.2, 1.7</td>
<td>0.3 (0.1, 0.5)</td>
<td>0.002*</td>
</tr>
<tr>
<td>ER:IR Ratio</td>
<td>0.78 ± 0.18</td>
<td>0.65, 0.85</td>
<td>0.72 ± 0.14</td>
<td>0.64, 0.85</td>
<td>0.06 (-0.02, 0.13)</td>
<td>0.119</td>
</tr>
</tbody>
</table>

* = Significant comparison within group at α = 0.05
REFERENCES


Risk Factors for Shoulder Injuries in Water Polo: a Cohort Study

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Background

Very limited investigations have been conducted exploring risk factors for injury in water polo players. A gap remains in the literature regarding identification of variables that should be considered as part of player screening evaluations.

Purpose

To estimate whether previous injury, changes in strength, range of motion (ROM) or upward scapular rotation (UR) are related to shoulder injuries in water polo players.

Study Design

Descriptive cohort study

Methods

Thirty-nine international-level players participated (19 males). Shoulder internal (IR) and external rotation (ER) peak torque was measured using an isokinetic device (CONtrex MJ). Shoulder ROM was measured passively using standard goniometry. Scapular UR was measured using a laser digital inclinometer. At baseline players were divided into groups: those with and without previous shoulder injuries. Independent t-tests and Mann-Whitney U tests were used to compare the study variables between groups. After nine months, a second analysis compared the same athletes, who were then grouped by those who had or had not sustained new injuries. Effect sizes were calculated with a Hedge's g. Chi squared analysis compared proportion of injured players with and without previous injury.

Results

Eighteen participants (46%) had previous injuries at baseline. Players with a previous injury showed higher peak torques for IR (0.62±0.15 vs 0.54±0.13 N/kg, p=0.04, g=0.60); larger loss of IR ROM (9.9±9.1 vs 4.1±7.5°, p=0.04, g=0.68), but no statistical difference in UR (p=0.70). After nine months, there were no statistical strength differences between groups. Loss of IR ROM was significantly higher in the injured group (9.8±9.8 vs 4.0±6.7°, p=0.04, g=0.68), as well as UR (15.0±5.0 vs 10.4±3.3°, p=0.01, g=0.81). History of previous injury was significantly related to developing a new injury (OR 6.5, p=0.02). Logistic regression found previous injury and UR most important contributors to injury risk.

Conclusions

Previous injury, changes in IR ROM and UR are related to new shoulder injuries in water polo, but further variables such as rest, training load, or psychosocial factors may explain
the incidence of new injuries.

Level of Evidence
Level 3

INTRODUCTION

Water polo is a popular aquatic contact sport, and has the highest rates of injuries amongst other aquatic disciplines during competitions (16.2% to 19.4%). Although the majority of observed traumatic injury incidence occur to the head and fingers during matches, the most common overuse injury area is the shoulder. In order to decrease shoulder injuries in water polo, a better understanding of their risk factors is necessary to target prevention measures.

Lack of shoulder range of motion (ROM) has been shown to correlate strongly with shoulder injuries in swimming and overhead throwing sports. Water polo players show greater ER, decreased IR, and increased total range of motion in their dominant shoulders compared to their contralateral side. However, Elliott found no statistical correlations between shoulder pain and ROM in a group of 13 male national team water polo players. In contrast, Hams et al. found that players in the injured group showed significantly less total range of motion (ER plus IR) (p<0.05). Thus, more evidence is needed to correlate injuries with ROM measures of the shoulder in water polo players.

Altered scapular posture is related to shoulder pain in throwing sports, and it is hypothesized that the "head up" swimming pattern typical during water polo can also lead to impingement syndromes. One group of authors found no differences between water polo players and healthy controls in scapular upward rotation (UR) using electromagnetic 3D kinematic measurements (frontal plane angle of the spine of the scapula vs a horizontal line). Two-dimensional measurements of UR have also shown good to excellent reliability, and have been implemented by other authors to assess water polo players. Mukhtyar et al. compared the scapular abduction position of healthy water polo players (n=16) to players with impingement symptoms (n=14) by measuring the distance between scapular angles and the spine after training. The group with shoulder impingement showed significantly decreased values for scapular abduction and UR (p<0.05) at 45° or more of shoulder abduction. However, Witwer et al. did not observe these patterns of decreased upward rotation in a cohort of 31 collegiate water polo players (12 males and 19 females) in a rested state.

Previous researchers have investigated strength, ROM, scapular alignment, throwing variables, and shooting volume as potential risk factors for shoulder injuries. However, only one investigation was performed prospectively on sub-elite players, and none in other age groups. Therefore, the causal relationship between injuries and these variables remains unclear. Strength and ROM were the only variables measured in relation to shoulder injury incidence. Additional understanding of risk factors is necessary to inform effective injury prevention strategies in this sport. Therefore, the purpose of this study was to estimate whether previous injury, changes in strength, ROM or UR are related to shoulder injuries in water polo players. A secondary objective was to compare sex differences among these risk factors. Given previous findings, it was expected that weaker players with less ROM and less upward rotation of the scapulae would be at higher risk of injuries.

METHODS

SUBJECTS

Nineteen male and twenty female water polo players from the Canadian senior national team were selected for this cohort study. Participants had to have a minimum of five years of experience, and be training full-time in a high-level competition environment (at least five practices per week). Subjects with a history of shoulder injury or surgery were included if they were able to participate fully in all team training sessions at the beginning of the study. A formal sample size calculation was not performed because all members of the senior national teams in Canada were recruited (n=39). Further recruitment would have required the addition of lower level players that did not represent the target population. Data were collected at the training center at the Institut National du Sport du Québec in Montreal, Canada. This study received ethics approval from McGill University Ethics Institutional Review Board, in compliance with the Helsinki Declaration. All participants signed informed consent to take part in the study.

PROCEDURES

Demographic data were collected for age, body mass index (BMI), hand dominance, player position and training setting. Shoulder passive ROM was assessed in ER and IR using a standard goniometer. Shoulder strength was assessed with an isokinetic device for ER and IR. Scapular UR was assessed with a digital inclinometer.
RANGE OF MOTION

Participants were positioned in supine, with the shoulder in 90° of flexion and abduction (Figure 1). A small lift was placed under the elbow to align the humerus parallel to the ground. The fulcrum was placed distally to the patient on the elbow, with the reference arm perpendicular to the arm and the measurement arm aligned with the styloid process of the ulna. The participant’s shoulder was then brought passively into the maximal tolerated ER, and a measure was taken at the end position. The shoulder was then brought back to the resting neutral position, and the procedure was repeated to take a second measurement. The evaluator then changed sides to measure the contralateral shoulder using the same procedure. Next, the evaluator returned to the starting side and measured shoulder IR twice using the same procedure, which was finally repeated on the contralateral shoulder.

Shoulder ER ROM was obtained by taking the average of the two measurements. This was repeated for IR. Shoulder total range of motion was calculated as the sum of both ER and IR for each shoulder. Internal rotation loss was defined as the difference between shoulder IR from the dominant side compared to the non-dominant side.27 External rotation gain was defined as the difference between shoulder ER of the dominant side with the non-dominant side.27 Similar methods for measuring shoulder ROM have demonstrated very good inter-rater (intra-class correlations of 0.97 (ICC); 95%CI=0.89,0.99) and intra-rater reliability (ICC=0.95; 95%CI=0.87,0.98).28

STRENGTH

Shoulder IR and ER strength was measured using a CON-TREX® isokinetic dynamometer (CON-TREX MJ; CMVA G, Dübendorf, Switzerland) with a protocol of 90°/s concentric/concentric contractions with a maximum torque tolerance of 250Nm sampled at 4000Hz. Participants were measured in supine with the shoulder placed in 90° of flexion and abduction to replicate the throwing position (Figure 2). All measurements were taken in the afternoon before practice to avoid testing in a fatigued state. Eccentric contractions were not employed to avoid muscle soreness prior to training. Participants were provided with an opportunity to perform 10 sub-maximal repetitions of IR and ER of the non-dominant side as a warm up. After a one minute break, participants were asked to "push against the machine as hard as [they] can" for five repetitions. Verbal encouragement was provided throughout the testing procedure. After a two minute break, the procedure was repeated on the dominant side.

Shoulder torque values provided by the CON-TREX® software were gravity-corrected. A custom RStudio29 script was written to filter only the values measured at the target test speed of 90°/s ± 0.5°/s. The peak value was identified as the maximum value recorded within this filtered subset and used for the rest of the analysis in the study. Measures of relative torque were calculated by dividing the absolute values by the participants’ body weight. Ratios were obtained by dividing the peak ER torques by the peak IR torques. Between-days repeatability of isokinetic dynamometers is very good to excellent for shoulder assessments (ICC = 0.85,0.97).30

SCAPULAR ALIGNMENT

Scapular UR was measured using a Halo™ digital inclinometer (model HG1, HALO Medical Devices, Australia) after performing the dynamometer testing and with the participant standing with their shoulder in a 90° of abduction position (Figure 3). Scapular orientation was measured in the frontal plane only, and measurement of upward rotation was estimated by placing the fulcrum on the superior angle of the scapula and estimating the angle between the tip of the acromion and the horizontal plane. The participants were given 30 seconds to bring their arms down to rest, and the measure was repeated after the participants performed another 90° abduction movement. This was then repeated for the contralateral shoulder. Scapular UR was calculated by taking the average of the two measurements. This method was described previously to be reliable (ICC
0.81–0.94), and the position of shoulder abduction at 90° was preferred to identify differences.

INJURY SURVEILLANCE

Injuries were defined in accordance with established consensus statements as any musculoskeletal injury or concussion for which the athletes required a consultation with a health care practitioner. In order to establish previous injury counts at baseline, a database of medical records was reviewed with a focus on shoulder injuries that had occurred in the prior 12 months. This database is linked with the participants’ electronic medical record (EMR), where every consultation with a sports medicine doctor, physiotherapist, or other health care practitioner had been entered and labelled for the corresponding injury accordingly. The EMR is maintained on a secure server with password encryption according to standards established by the Collège des Médecins du Québec. For the new injury incidence, an online surveillance program Hexfit™ (Hexfit Solutions Inc, Canada) was used to collect daily information on training loads and overuse injuries longitudinally for nine months of normal training and competitions. The system automatically flagged athletes who reported pain during training, and they were then contacted by the lead researcher to confirm that the injury qualified as per the study inclusion criteria. This method has been shown to be reliable in the past with a population of water polo players.

ANALYSIS

Given the small sample available for this study, groups were dichotomized at baseline by those who had sustained a previous shoulder injury and those who had not. An additional analysis was done after nine months follow-up to compare players with new injuries versus no new injuries. Most variables showed close to normal distributions, except for strength variables. Therefore, independent t-tests were applied to compare dominant shoulder ROM and UR variables between healthy and injured players. Range of motion comparisons were made for range into ER and IR, total range of motion, ER gain and IR loss compared to the non-throwing shoulder. Mean UR was compared for scapular alignment differences. Mann-Whitney U tests compared relative dominant shoulder strength and strength ratios between the healthy and injured groups. The variables compared were average relative peak torque in ER and IR as well as ER:IR ratios. Effect sizes were calculated to compare group means with a Hedges g correction approach given the sample size, with small effect described as values <0.2, medium effect <0.5 and large effects ≥0.8. Male and female players were compared as groups using the same approach. A chi-square analysis compared the proportions of players with a new injury vs a previous injury.

A logistic regression was performed to estimate the relative impact of the risk factors on new injuries in an exploratory analysis. The dependent variable was the development of a new injury over the nine month follow-up (1=injury, 0= no injury). In the first step, a history of previous injury was entered as a confounding variable (1=previous injury, 0=no previous injury). Next, a strength, ROM or UR variable was entered to determine if they related to the development of injuries over the nine month follow-up. Separate models were created for each strength, ROM or UR variable. The optimal model was decided as that which included only significant coefficients, provided the highest pseudo-R² value, and minimized the residual deviance. Odds ratios with 95% confidence intervals (CI) were also calculated for the variables included in the model based on the logit of the coefficients.

RESULTS

Nearly half of the participants in the study (18/39) had sustained a previous shoulder injury at baseline. Demographic variables were similar for the previously injured vs previously healthy groups in terms of age, sex, BMI, hand dominance, and training setting (Table 1). However, there were no goalies with previous shoulder injuries.

Observations comparing dominant to non-dominant sides showed increased dominant shoulder ER ROM (105±11° vs 98±11°, p=0.01) and decreased IR (53±11° vs 59±10°, p=0.01). There was however no difference in total range of motion (p=0.98). Furthermore, there were no significant differences in strength (p=0.58-0.70) or UR (p=0.99). Findings for group comparisons of strength, ROM and UR can be found in Table 2 and Table 3.

The previously injured group showed no significant differences in shoulder ROM into ER, IR or in total range of motion. However, athletes with a previous injury showed greater IR loss on the dominant shoulder (moderate ES g=0.68, 95%CI=0.03, 1.34) and higher mean relative IR strength (moderate effect size ES), g=0.60; 95%CI=0.05, 1.25). The ER:IR ratios were not significantly different between groups (Table 2). No significant difference was observed in UR.

At the nine month follow-up, players were once again divided into two groups based on the presence of a new shoulder injury (Table 3). Three players from the men’s team quit the program during the study, but had already developed new shoulder injuries before they left. Therefore, they were
Table 1: Baseline demographic data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Previous Injury (n=18)</th>
<th>No Previous Injury (n=21)</th>
<th>New Injury (n=19)*</th>
<th>No new injury (n=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Age, years (SD)</td>
<td>23.4 (4.3)</td>
<td>22.8 (2.9)</td>
<td>22.5 (4.1)</td>
<td>22.7 (3.0)</td>
</tr>
<tr>
<td>Male (%)</td>
<td>10 (56%)</td>
<td>9 (43%)</td>
<td>9 (47%)</td>
<td>10 (50%)</td>
</tr>
<tr>
<td>Mean BMI (SD)</td>
<td>25.2 (3.2)</td>
<td>24.7 (2.2)</td>
<td>25.0 (3.2)</td>
<td>24.9 (2.2)</td>
</tr>
<tr>
<td>Hand dominance (frequency)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>17</td>
<td>20</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Left</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Player position (frequency)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goalie</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Set</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Driver</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Training setting (frequency)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>National center</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Professional</td>
<td>9</td>
<td>7</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>College</td>
<td>9</td>
<td>7</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

*The groups were classified after the nine month follow-up into those who developed prospective injuries and those that remained healthy.

Table 2: Mean physical factors of the dominant shoulder for athletes with previous injuries and results of statistical comparisons.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Previous injury (n=18)</th>
<th>No previous injury (n=21)</th>
<th>Significance (p-value)</th>
<th>Effect size g [95% CI]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER (Nm/kg)</td>
<td>0.43 (0.10)</td>
<td>0.38 (0.11)</td>
<td>0.12</td>
<td>0.45 [-0.20, 1.09]</td>
</tr>
<tr>
<td>IR (Nm/kg)</td>
<td>0.62 (0.15)</td>
<td>0.54 (0.13)</td>
<td>0.04</td>
<td>0.60 [-0.05, 1.25]</td>
</tr>
<tr>
<td>ER/IR ratio</td>
<td>0.70 (0.10)</td>
<td>0.72 (0.11)</td>
<td>0.60</td>
<td>-0.16 [-0.79, 0.48]</td>
</tr>
<tr>
<td>ROM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER (°)</td>
<td>105.1 (11.0)</td>
<td>104.8 (11.6)</td>
<td>0.93</td>
<td>-0.07 [0.61, 0.67]</td>
</tr>
<tr>
<td>IR (°)</td>
<td>52.0 (10.2)</td>
<td>52.9 (11.7)</td>
<td>0.80</td>
<td>-0.08 [-0.72, 0.56]</td>
</tr>
<tr>
<td>Total rotation (°)</td>
<td>157.1 (12.5)</td>
<td>157.7 (14.7)</td>
<td>0.90</td>
<td>-0.04 [-0.68, 0.60]</td>
</tr>
<tr>
<td>ER gain (°)</td>
<td>7.7 (8.3)</td>
<td>5.1 (8.6)</td>
<td>0.35</td>
<td>0.30 [-0.34, 0.94]</td>
</tr>
<tr>
<td>IR loss (°)</td>
<td>9.9 (9.1)</td>
<td>4.1 (7.5)</td>
<td>0.04</td>
<td>0.68 [0.03, 1.34]</td>
</tr>
<tr>
<td>Scapular alignment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UR (°)</td>
<td>11.4 (3.0)</td>
<td>11.8 (3.7)</td>
<td>0.70</td>
<td>-0.12 [-0.76, 0.52]</td>
</tr>
</tbody>
</table>

ER = external rotation, IR = internal rotation, ER:IR = ratio of external over internal rotation, ROM = range of motion, UR = upward rotation.

classified into the group with new injuries (n=19). A chi-square test confirmed that the players that had a previous injury were significantly more likely to develop new injuries (71.4% vs 27.8%, p=0.02). Furthermore, dominant shoulder IR loss was significantly higher in the group with new injuries (p=0.04, ES=0.68). Relative strength values were not different between groups, but UR was significantly greater in the group with new injuries (p<0.01, ES=0.81).

Sex comparisons showed that female players demonstrated higher total range of motion in rotation (p=0.02, ES g=0.75). Males were much stronger than the female players in both ER and IR, respectively (p<0.01, large ES g=2.03, 2.04), but ER:IR ratios were not different (Supplemental Table 1). No other variables were significantly different between sexes.

The best model fit to explain new injuries included previous injuries and UR (Table 4). This model minimized residual deviance (37.04) and maximized the pseudo-R² value using the Nagelkerke method (R²=0.47). The odds ratios (OR) for history of previous injury are 6.5, (95%CI=1.6, 26.4), and increased UR was related to more likelihood of developing a new injury (OR=1.5, 95%CI=1.1, 2.0) after accounting for a previous injury. No other variables were significantly related to new injuries in the logistic regression analyses.

DISCUSSION

Overall, this study showed that shoulder ER and IR ROM, strength, and UR are risk factors associated with shoulder injuries in water polo. At baseline, players with previous injuries demonstrated statistically significantly increased IR strength and loss of IR ROM on the dominant side. After nine months (and redistribution into injured/uninjured groups) strength measurements were not significantly different, but rather IR loss (greater in injured athletes) and
Table 3: Mean physical factors of the dominant shoulder for athletes with new injuries** and results of statistical comparisons

<table>
<thead>
<tr>
<th>Variable</th>
<th>New injury (n=19)</th>
<th>No new injury (n=20)</th>
<th>Significance (p-value)</th>
<th>Effect size g [95% CI]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER (Nm/kg)</td>
<td>0.40 (0.11)</td>
<td>0.41 (0.10)</td>
<td>0.92</td>
<td>-0.14 [-0.77, 0.50]</td>
</tr>
<tr>
<td>IR (Nm/kg)</td>
<td>0.59 (0.14)</td>
<td>0.56 (0.15)</td>
<td>0.52</td>
<td>0.18 [-0.46, 0.81]</td>
</tr>
<tr>
<td>ER/IR ratio</td>
<td>0.68 (0.12)</td>
<td>0.74 (0.08)</td>
<td>0.09</td>
<td>-0.61 [-1.26, 0.04]</td>
</tr>
<tr>
<td>ROM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER (°)</td>
<td>104.9 (10.9)</td>
<td>105.1 (11.7)</td>
<td>0.96</td>
<td>-0.02 [-0.65, 0.62]</td>
</tr>
<tr>
<td>IR (°)</td>
<td>49.9 (10.1)</td>
<td>54.9 (11.4)</td>
<td>0.16</td>
<td>-0.45 [-1.09, 0.19]</td>
</tr>
<tr>
<td>Total rotation (°)</td>
<td>154.8 (12.6)</td>
<td>160.0 (14.3)</td>
<td>0.24</td>
<td>-0.37 [-1.01, 0.27]</td>
</tr>
<tr>
<td>ER gain (°)</td>
<td>7.7 (8.4)</td>
<td>5.0 (8.5)</td>
<td>0.33</td>
<td>0.31 [-0.33, 0.95]</td>
</tr>
<tr>
<td>IR loss (°)</td>
<td>9.8 (9.8)</td>
<td>4.0 (6.7)</td>
<td>0.04*</td>
<td>0.68 [0.03, 1.33]</td>
</tr>
<tr>
<td>Scapular alignment</td>
<td>UR (°)</td>
<td>13.0 (3.0)</td>
<td>10.4 (3.3)</td>
<td>0.01*</td>
</tr>
</tbody>
</table>

*Strength variables were not normally distributed and groups were compared with Mann-Whitney test.

**Three male athletes quit water polo during the study follow-up period, and were included in the prospective injured group because they had prior injuries.

ER = external rotation, IR = internal rotation, ER:IR = ratio of external over internal rotation, ROM = range of motion, UR = upward rotation.

Table 4: Significance of risk factors in a logistic regression with previous injury as a confounder

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>p-value</th>
<th>R² (Nagelkerke)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex=male</td>
<td>-0.42</td>
<td>0.57</td>
<td>0.25</td>
</tr>
<tr>
<td>Relative external rotation strength</td>
<td>-4.54</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>Relative internal rotation strength</td>
<td>-0.72</td>
<td>0.78</td>
<td>0.24</td>
</tr>
<tr>
<td>Ratio external/internal rotation strength</td>
<td>-7.07</td>
<td>0.08</td>
<td>0.34</td>
</tr>
<tr>
<td>External rotation flexibility</td>
<td>-0.01</td>
<td>0.92</td>
<td>0.24</td>
</tr>
<tr>
<td>Internal rotation flexibility</td>
<td>-0.05</td>
<td>0.15</td>
<td>0.30</td>
</tr>
<tr>
<td>Total rotation flexibility</td>
<td>-0.03</td>
<td>0.22</td>
<td>0.28</td>
</tr>
<tr>
<td>External rotation gain</td>
<td>0.03</td>
<td>0.51</td>
<td>0.25</td>
</tr>
<tr>
<td>Internal rotation loss</td>
<td>0.07</td>
<td>0.17</td>
<td>0.29</td>
</tr>
<tr>
<td>Scapular upward rotation</td>
<td>0.39</td>
<td>0.01</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Previous injury was entered as the first confounder, and then a separate model was created with each variable above.

UR showed a positive association. Largely, the most important predictor of new injury was the presence of a previous injury, with a 6.5 times increased odds of developing a new injury with this risk factor. Finally, male players showed higher strength values and less total ROM than their female counterparts.

Measures of relative IR strength were the only strength variable correlated with previous injury, and no strength variables were associated with new injury. In their group, Hams et al35 found that high-level Australian water polo players with lower isometric strength had an association with new injuries. In the present study, relative IR strength was significantly higher for the group with previous injuries, but was not related to new injuries. The higher values of dominant shoulder strength for athletes with previous injuries may reflect that they may have been more likely to be performing targeted strengthening exercises to avoid new injuries, and thus demonstrated stronger test values. Consistent with Hams et al,11 ER:IR strength ratios were not associated with new injuries, which suggests that asymmetries in rotator cuff strength may not be as widely present as was once suspected in this population.3

A greater loss of IR ROM was significant in the injured groups at baseline and after nine months. All other measures of ROM were otherwise similar between healthy and injured groups, and consistent with previous authors.8,18 The loss of IR ROM may impact the players’ ability to decelerate the overhead throws, and put more mechanical stress on the rotator cuff muscles. Over time, this can lead to pathologies such as those observed in this population with MRI which affect the postero-superior area of the gleno-humeral joint.36–38 A loss of shoulder IR ROM may also decrease the mechanical efficiency of the pulling motion of swimming, where players would need to increase scapular
tilting to bring the arm in an optimal mechanical position. This in turn can lead to an increase in mechanical stress on the anterior structures of the shoulder such as the acromioclavicular joint and the brachii.\textsuperscript{39}

The injured group at follow-up showed a significantly higher dominant shoulder mean UR. This variable was also a key factor in the logistic regression model, showing that increasing UR contributes to the risk of sustaining an injury. Based on previous studies, it would rather have been expected to find decreased values in the injured group.\textsuperscript{40} These findings may be the result of limiting measurement to static positions where the range of values observed was narrow. Active movement measured with three-dimensional kinematic equipment would be more precise. Furthermore, Mukhtyar et al\textsuperscript{23} found significant differences between injured and non-injured water polo players only when the players were in a fatigued state after training. The task of repeated shoulder rotations on the isokinetic dynamometer may not have stressed the scapulo-thoracic musculature sufficiently, and may not have induced the type of fatigue expected after water polo training.

The male players showed significantly higher relative strength compared to the female players in both ER and IR. This can be the result of different training methods, or a reflection of the more physical demands of the sport in the men’s style of play. Given that female players use a smaller and lighter ball, this may decrease the impact of lower strength on their ability to generate powerful overhead throws, but comparisons between sexes are lacking in the literature. The increased ROM that the female players demonstrated may be advantageous to accelerate the ball over a larger distance before throwing. However, this increased ROM may be an added risk factor for specific types of shoulder pathologies affecting joint stability.\textsuperscript{41}

The study is limited in its generalizability given the small sample size. However, this sample included the entire population of international level water polo players in Canada, and the findings remain important for this group. A twelve-month follow-up was planned, but confinement due to COVID-19 pandemic interrupted all training activities after nine months. Secondly, a test of eccentric ER strength using the isokinetic dynamometer would allow to calculate a functional ratio of strength at the shoulder that resembles the throwing motion more closely (concentric IR to eccentric ER. In this study, this method was not chosen in order to limit fatigue before training sessions. Further studies investigating strength should consider this approach. Third, the methodology for measuring UR was optimal in the training setting, but it cannot yield information about active range of motion. In addition to taking all the measurements after training, future research should include a more substantial fatigue protocol to explore the conclusions of Mukhtyar et al.\textsuperscript{23} Finally, other important risk factors were not considered, such as training volume and psychological factors.\textsuperscript{42}

CONCLUSION

In conclusion, the results of the current study indicate that a history of previous injury, as well as measures of shoulder IR and UR were most strongly associated with risk for sustaining a new injury in a sample of international level players of both sexes. This study adds to a small body of Level 2\textsuperscript{43} literature on risk factors for shoulder injuries in water polo. These findings indicate that monitoring shoulder ROM, UR, and strength should be considered as core elements of an injury prevention program for water polo players. Additional studies which investigate the effectiveness of different protocols to optimize strength ratios and ROM are needed to guide these programs.

CONFLICTS OF INTEREST

None to declare

FUNDING

Research, Innovation and Dissemination of Information Program (PRIDI)

Submitted: January 23, 2021 CDT, Accepted: April 17, 2021 CDT
REFERENCES


Supplementary Materials

Background
Post-professional residency training in sports physical therapy has undergone rapid growth since its inception over 20 years ago with 58 programs currently accredited.

Purpose
The purpose of this survey was to describe and contrast the demographics, motivations, and selection influences from the perspective of both potential training applicants and program faculty.

Study Design
Cross-sectional descriptive survey

Methods
156 physical therapists identified as stakeholders in sports residency and fellowship training were invited to participate in a 115-item survey. Descriptive measures of central tendencies to describe the data and Mann Whitney Rank Sum tests were used to detect differences between the perspectives of applicants and faculty.

Results
50 program faculty and 57 applicants responded to the survey for a 69% response rate. Motivations for post-professional training categorized as extremely important were largely intrinsic behavioral modifiers centering on improved knowledge, skills, and outcomes while satisfying a passion for sports specialty training and enhancing job opportunities in the field. 7 of the 10 highest rated application motivations were rated as significantly more important by applicants than faculty members \((p<0.05)\). The two most highly rated influences for choosing to apply to a specific residency site were the perception for subsequent job opportunities and perceived relationship and qualifications with the residency director and staff. The importance of job opportunities in sports PT was rated much higher by the applicant than the faculty \((p=0.003)\).

Conclusions
While the motivations for residency training may be slightly different between groups the importance of information acquisition and methods for residency selection criteria seem more congruent. Residency faculty may underestimate the importance of some of the most important motivations that prompt interest in residency training. Recognition of these factors may alter the presentation and content design of residency curriculums.
INTRODUCTION

Physical therapy residency and fellowship training in the United States is a recognized and promoted path to afford advanced training opportunities in specialty practice areas. The content of the specialty expertise is captured by the description of residency practice and governed by the American Board of Residency and Fellowship Education. As of January of 2021 there were 58 accredited sports physical therapy residency programs with an additional 14 programs in a developmental or candidacy status. Additionally, there are nine fellowship training programs relevant to the practice of sports physical therapy (performing arts, upper extremity athlete, and D1 athlete) and three more fellowship programs in the development stage. Residency and fellowship programs exist to improve skill and expertise, provide structured mentoring, expose the trainee to event coverage, and potentially offer an accelerated track to attaining clinical specialist recognition.

In part, the popularity and exponential growth in sports physical therapy residency and fellowship training over the past two decades may be attributable to the opportunity for young, less experienced clinicians to interact with, learn from, and network with like-minded advanced practitioners. What is less clear is what specifically motivates clinicians to pursue this optional, post-professional training in this specific field of physical therapy. Even though residents and fellows usually have a high work demand and are compensated at a lower rate, the number of qualified applicants for these training opportunities far exceed the number of positions available. Even more striking is that this strong interest exists despite increasing stress over educational debt and the recognized value of return on investment analysis in regards to debt to income ratios. Despite all these factors, interest in sports physical therapy residency training remains very high. In light of this, programs providing advanced sports physical training often have a deep field of applicants from which to make a candidate selection. It is unclear what motivations, attributes, and attitudes make a residency or fellowship application competitive. It would be advantageous to both the program and applicant to know what characteristics enhance the match between these two entities of interest. Ideally, the application process will maximize the likelihood of the optimal training opportunity being provided by the strengths of particular training program.

Given the importance of mentorship and direct, collegial communication between the resident and program faculty mentor(s), this study aims to evaluate the characteristics, components, and elements of the residency experience that are important to ensure a good match for both parties. The purpose of this study was to describe and contrast the demographics, motivations, and selection influences from the perspective of both potential training applicants and program faculty. This purpose has four principal objectives. First, to better understand the factors that motivate the pursuit of sports residency training and contrast how important these factors are to resident applicants versus faculty providers. Second, to identify factors that influence the match (application to or acceptance of residents to a training program). Third, to identify the importance and preferred methods to acquire, exchange, and disseminate information about the program between the applicant and provider. And finally, provide insight regarding the factors and criterion used to differentiate and select applicants for residency positions.

METHODS

An online cross-sectional survey was designed, further described below, to collect information regarding the motivations, attitudes, and attributes of individuals involved with sports physical therapy residency and fellowship education.

PARTICIPANTS

Two groups of individuals from a sample of convenience were invited via email during May of 2020. All physical therapists listed as residency or fellowship directors on the directory provided by the American Board of Physical Therapy Residency and Fellowship Education (ABPTRFE) website as well as all members of the American Academy of Sports Physical Therapy (AASPT) Specialization special interest group was included. Because Residency and Fellowship Physical Therapy Centralized Activation Service (RF-PTCAS) and the ABPTRFE are prohibited from disseminating personal contact information on residency applicants and graduates we asked these 156 individuals to assist with distributing the invitation link. They were asked to forward the email invitation to all current applicants and all past graduates. The goal was to obtain at least 50 responses from both resident applicant and faculty member categories. This would represent at least an average of two responses from each program accredited at the time of the survey. Based on a 95% confidence level, at least 105 responses (67% response rate) were needed from known invited group members to bring the statistical random sampling margin of error to within ±5%.

SURVEY ADMINISTRATION

Study data were collected and managed using REDCap electronic data capture tools hosted at UT Southwestern Medical Center in Dallas, TX. REDCap (Research Electronic Data Capture) is a secure, web-based application designed to support data capture for research studies, providing: 1) an intuitive interface for validated data entry, 2) audit trails for tracking data manipulation and export procedures, 3) automated export procedures for seamless data downloads to common statistical packages, and 4) procedures for importing data from external sources.

The invitation cover letter described the study’s purpose, emphasized anonymity through aggregate-only reporting, and stated that voluntary consent was designated by responding to the survey link. The instructions reminded respondents that there were no correct or preferred opinions and that the results would be used by AASPT and ABPTRFE leadership to develop initiatives and services to promote post-professional sports physical therapy education and training. After the initial email was extended, follow-up requests were sent at one and two weeks. The survey was closed when the final invitation did not generate more than
a 10% response increase. Before dissemination, the survey was reviewed and determined to meet exempt criteria by the Institutional Review Board at UT Southwestern Medical Center in Dallas, TX. All responses were anonymous.

TOOL DEVELOPMENT

The survey tool was initially developed by an AASPT member with 40 years of academic, residency, and sports specialty clinical experience. Previous studies with similar objectives were also used as a reference to inform survey organization and format.1,9,14,15,19 The initial survey draft was piloted with four AASPT members familiar with professional education. Their critique regarding the survey’s questions, organization, and readability enhanced the face validity of the content. Based on this collective input, the survey was modified and finalized for distribution. The final data collection instrument was a 116-item questionnaire.

The general categories for data capture on the survey were divided into five sections:. For sections two through five, the survey respondent ranked each factor on an ordinal scale from 0-5 ranging from not important to extremely important.

Section 1: Twenty-five demographic questions regarding respondent’s age, sex, ethnicity, marital status, geographical location, membership status, clinical experience, educational background, credentials, athletic interests, residency/fellowship involvement, and employment title and responsibilities.

Section 2: Fifteen items that solicited the applicant’s motivations and faculty respondent’s perception on the importance of factors that motivate the pursuit of residency education and training.

Section 3: Forty-five items that solicited the applicants and faculty’s opinions on the variables that influence the application and/or acceptance to a specific residency or fellowship training site.

Section 4: Eleven items regarding the importance of various methods to acquire, exchange, and disseminate specific details inherent to individual residency programs from the perspective of both applicants and providers.

Section 5: Thirteen items that solicited opinions regarding factors relevant to the match and selection of a resident to a particular training program.

DATA ANALYSIS

Measures of central tendencies were derived using a spreadsheet generated from a Microsoft Excel Data Analysis, 2010 package to describe the demographic profile of the respondents. Scores on each item, regardless of section, were calculated from the sum of rating values for each question. Based on distributions of the sum, Mann-Whitney Rank Sum tests from an on-line program at www.vassarstats.net were used to detect differences between the perspectives of applicants and faculty with a significance level of p < 0.05 being considered significant.20 Ordinal rankings of importance were created based on the median percentiles for both groups for each category of assessment. Factors characterized as “not important” were items that ranked in the bottom 20% percentile, very important in the top 20% percentile, and extremely important in the top 20% percentile.

RESULTS

The 156 invitations resulted in 157 responses to the survey. Fifty-seven residents or residency applicants and 50 residency/fellowship program faculty members completed the survey for a 69% known response. Fifty additional surveys were received in which the respondent indicated they had not been involved in a residency or fellowship training program as an applicant or faculty member. These responses were not used for the statistical analysis. 71% of all the respondents were male with a mean age of 35.1 ± 9.4. All were AASPT members and represented 88% of the states with accredited residency programs. As anticipated there was a significant difference between faculty and applicants in regards to age (40.0 ± 9.6 vs. 26.9 ± 2.1; p < 0.0001), experience (7.7 ± 9.4 vs. 0.25 ± 0.49 years; p < 0.0001), entry-level professional degree (52% DPT vs 100% DPT), marital status (80% vs. 26% married), and athletic training licensure (34% vs.14% Athletic Trainer, Certified [ATC]). There was no difference between groups in regards to sex (74% vs 68% male; p = 0.62), AASPT membership status (both 100%), race/ethnicity (both 94% white of those reporting), personal competitive athletic background (both 100%), Certified Strength and Conditioning Specialist credential (CSCS) (44% vs 40%) or perception in ideal clinical productivity (30.2 ± 12.7 vs. 29.4 ± 11.5 daily units charged; p = 0.65). (Table 1)

Table 2 details the importance of the factors that may motivate the pursuit of residency education and training. Of the 15 factors surveyed, eight were rated as significantly more important to the resident than to the program faculty (p ≤ 0.05). This included seven of the 10 most important factors. Motivations that were rated as extremely important by both parties included the acquisition of clinical skills, knowledge, and critical thinking under the guidance of an accomplished mentor while fulfilling a personal passion and desire to practice in the sports physical therapy field.

Table 3 details the applicant’s and faculty’s opinions on what variables influence the application and/or acceptance to a specific residency or fellowship training site. Of the 45 variables surveyed there were four rated as significantly more important to the resident/fellow applicant than to the program faculty and four additional variables that were significantly more important to the program faculty than resident/fellow applicants. The only variable rated as extremely important was the potential for future job opportunities by the resident (4.52 vs 3.81; p < 0.005).

Multiple other factors were rated as very important in influencing an applicant to apply to or accept an offer from a particular program with a premium on the overall perception from the interview experience in regards to the faculty’s qualifications, stability, and mentoring abilities. Additionally, the clinic infrastructure, learning opportunities, and ability to work in specific sports were highly valued. The variables rated more important to the resident than the program faculty were the future job opportunities, a preference for an academic environment with teaching oppor-

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Table 1. Demographic characteristics of survey respondents

<table>
<thead>
<tr>
<th>Demographic Characteristic</th>
<th>Residents/Applicants (n=57)</th>
<th>Directors/Faculty (n=50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (mean ±SD) (range)</td>
<td>26.9 ± 2.1 (24-33)</td>
<td>40.0 ± 9.6 (29-72)</td>
</tr>
<tr>
<td>Sex</td>
<td>39 male; 18 female</td>
<td>37 male; 13 female</td>
</tr>
<tr>
<td>APTA member (% yes)</td>
<td>57/57 (100%)</td>
<td>50/50 (100%)</td>
</tr>
<tr>
<td>AASPT member (% yes)</td>
<td>57/57 (100%)</td>
<td>50/50 (100%)</td>
</tr>
<tr>
<td>Race</td>
<td>50 White (not of Hispanic origin) 4 (Asian or Pacific Islander) 2 Hispanic/Latino 1 Other</td>
<td>47 White (not of Hispanic origin) 2 Hispanic/Latino 1 Asian or Pacific Islander</td>
</tr>
<tr>
<td>Marital Status</td>
<td>42 single (74%) 15 married (26%)</td>
<td>40 married (80%) 7 single (14%) 1 divorced (2%) 1 widowed (2%) 1 prefer not to answer (2%)</td>
</tr>
<tr>
<td>Physical Therapy School Location</td>
<td>23 unique states</td>
<td>21 unique states</td>
</tr>
<tr>
<td>Experience (yrs) (mean ± SD) (range)</td>
<td>0.25 ± 0.49 (0-2)</td>
<td>7.7 ± 9.4</td>
</tr>
<tr>
<td>Entry Level Degree</td>
<td>57 DPT (100%)</td>
<td>26 DPT (52%) 17 Masters (34%) 6 Baccalaureate 12% 1 Certificate (2%)</td>
</tr>
<tr>
<td>Highest Degree</td>
<td>57/57 no further degrees (100%)</td>
<td>42 no further degrees (84%) 9 tDPT (18%) 6 Post-Doctoral (12%)</td>
</tr>
<tr>
<td>Personal Competitive Athletic Background</td>
<td>57/57 (100%)</td>
<td>50/50 (100%)</td>
</tr>
<tr>
<td>Youth Athlete</td>
<td>43/57 (75%) 34/57 (60%)</td>
<td>38/50 (76%) 28/50 (56%)</td>
</tr>
<tr>
<td>High School Athlete</td>
<td>31/57 (54%) 2/57 (4%)</td>
<td>26/50 (54%) 1/50 (2%)</td>
</tr>
<tr>
<td>Collegiate Athlete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Professional Athlete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possess Additional Relevant Certifications</td>
<td>27/57 (47%)</td>
<td>45/50 (90%)</td>
</tr>
<tr>
<td>Job Title</td>
<td>36/57 (63%) 12/57 (21%) Staff Clinician 5/57 (9%) Student Physical Therapist 4/57 (7%) Other</td>
<td>17/50 (34%) Supervisor/Director 16/50 (32%) Staff Clinician 13/50 (26%) Faculty 4/50 (8%) Administrator/Manager/Owner</td>
</tr>
<tr>
<td>Number of Residency Applications Submitted</td>
<td>4.6 ± 2.3</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

| Attributes, Attitudes, and Motivations of Personnel Involved with Sports Physical Therapy Residency Training

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Table 2. Values that motivate the pursuit of residency education and training

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Categorical Ranking</th>
<th>Median Category</th>
<th>Mean</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain knowledge, skills, and expertise in the practice of sports physical therapy</td>
<td>Residents</td>
<td>VI – EI</td>
<td>EI</td>
<td>4.83 ± 0.38</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.79 ± 0.46</td>
<td></td>
</tr>
<tr>
<td>Enhance clinical reasoning and critical thinking skills</td>
<td>Residents</td>
<td>VI – EI</td>
<td>EI</td>
<td>4.81 ± 0.40</td>
<td>0.02*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.58 ± 0.58</td>
<td></td>
</tr>
<tr>
<td>Fulfill passion and desire to practice sports physical therapy</td>
<td>Residents</td>
<td>VI – EI</td>
<td>EI</td>
<td>4.77 ± 0.42</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.66 ± 0.52</td>
<td></td>
</tr>
<tr>
<td>Enhance the ability to examine, diagnose, prognose, and improve patient outcomes</td>
<td>Residents</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.60 ± 0.62</td>
<td>0.02*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>VI</td>
<td>4.33 ± 0.69</td>
<td></td>
</tr>
<tr>
<td>Enhance career advancement and future job opportunities</td>
<td>Residents</td>
<td>MI – EI</td>
<td>EI</td>
<td>4.56 ± 0.71</td>
<td>0.02*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>VI</td>
<td>4.31 ± 0.68</td>
<td></td>
</tr>
<tr>
<td>Access to an accomplished mentor to provide feedback and boost confidence</td>
<td>Residents</td>
<td>MI – EI</td>
<td>EI</td>
<td>4.52 ± 0.73</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>EI</td>
<td>4.54 ± 0.62</td>
<td></td>
</tr>
<tr>
<td>Enhance the ability to use current best evidence patient management strategies</td>
<td>Residents</td>
<td>SI – EI</td>
<td>EI</td>
<td>4.51 ± 0.66</td>
<td>0.03*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>VI</td>
<td>4.29 ± 0.69</td>
<td></td>
</tr>
<tr>
<td>Enhance future leadership opportunities within the field of sports physical therapy</td>
<td>Residents</td>
<td>MI – EI</td>
<td>VI</td>
<td>4.12 ± 0.81</td>
<td>0.001*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.76 ± 0.72</td>
<td></td>
</tr>
<tr>
<td>Validate a commitment to lifelong learning</td>
<td>Residents</td>
<td>NI – EI</td>
<td>VI</td>
<td>4.09 ± 0.108</td>
<td>0.01*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.73 ± 0.96</td>
<td></td>
</tr>
<tr>
<td>Contribute to the evolution of the physical therapy profession</td>
<td>Residents</td>
<td>NI – EI</td>
<td>VI</td>
<td>4.04 ± 0.93</td>
<td>0.02*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.54 ± 0.90</td>
<td></td>
</tr>
<tr>
<td>Fast track to sports specialization credential</td>
<td>Residents</td>
<td>NI – EI</td>
<td>VI</td>
<td>3.60 ± 0.135</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>4.09 ± 0.86</td>
<td></td>
</tr>
<tr>
<td>Enhance the ability to conduct and interpret research</td>
<td>Residents</td>
<td>NI – EI</td>
<td>SI</td>
<td>3.47 ± 0.97</td>
<td>0.05*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.20 ± 0.71</td>
<td></td>
</tr>
<tr>
<td>Enhance the potential for future income</td>
<td>Residents</td>
<td>NI – EI</td>
<td>SI</td>
<td>3.40 ± 0.110</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.41 ± 0.89</td>
<td></td>
</tr>
<tr>
<td>Gain recognition from physicians or other types of sports healthcare providers</td>
<td>Residents</td>
<td>NI – EI</td>
<td>SI</td>
<td>3.23 ± 1.12</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.29 ± 0.89</td>
<td></td>
</tr>
<tr>
<td>Gain recognition from other physical therapists</td>
<td>Residents</td>
<td>NI – EI</td>
<td>SI</td>
<td>2.93 ± 0.109</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.20 ± 0.76</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 details the perceived value of 11 methods to acquire exchange and disseminate information about residency and fellowship programs. Both cohorts found the interview day to be the most important mechanism to reveal specific details inherent to individual residency programs. Other areas rated as very important included access to the program director’s phone number and email contact, website content, RF-PTCAS synopsis and links, and potential contact with previous or current residents or fellows. The opportunity for applicants to contact previous or current residents was rated significantly higher by faculty than applicants (p = 0.04). Providing printed materials with residency program information was rated significantly lower by the applicant than the faculty (p = 0.04).

The most consistent area of agreement between faculty and applicant respondents was in the area of factors that are important to the match and selection of a resident to a particular training program. Two areas that were rated as extremely important by both groups were the interview performance and letters of recommendation. There was also concurrence at the other end of the importance spectrum with the past and future geographical location preferences rated as minimally important. The one area in which there was a difference in opinion was the perception of the like-
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Categorical Ranking</th>
<th>Median Category</th>
<th>Mean</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future job opportunities</td>
<td>Residents</td>
<td>MI - EI</td>
<td>EI</td>
<td>4.32 ± 1.04</td>
<td>0.003*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.81 ± 0.94</td>
<td></td>
</tr>
<tr>
<td>Perceived relationship between resident(s) and program director/faculty</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.30 ± 0.85</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.19 ± 0.70</td>
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<tr>
<td>Impression and qualifications of residency program faculty and clinical personnel</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.05 ± 0.72</td>
<td>0.27</td>
</tr>
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<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.21 ± 0.71</td>
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<tr>
<td>Advice from trusted mentor or colleague</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.04 ± 0.80</td>
<td>0.18</td>
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<td></td>
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<td>MI - EI</td>
<td>VI</td>
<td>4.27 ± 0.71</td>
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<td>Overall interview experience</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.00 ± 0.87</td>
<td>0.32</td>
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<td>MI - EI</td>
<td>VI</td>
<td>4.19 ± 0.64</td>
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<tr>
<td>Perceived stability of department or clinic that is sponsoring residency program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.96 ± 1.03</td>
<td>0.06</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.79 ± 0.98</td>
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<td>Additional or supplemental learning opportunities made available and/or required (continuing ed classes, grand rounds, journal clubs, etc)</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.93 ± 1.05</td>
<td>0.02*</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.66 ± 0.89</td>
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<tr>
<td>Impression and qualifications of residency program director</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.86 ± 0.83</td>
<td>0.49</td>
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<td></td>
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<td>MI - EI</td>
<td>VI</td>
<td>3.94 ± 0.86</td>
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<td>Personal interactions (in person or electronic) with previous and/or current residents</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.84 ± 1.08</td>
<td>0.06</td>
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<td></td>
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<td>MI - EI</td>
<td>VI</td>
<td>3.73 ± 0.68</td>
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<tr>
<td>Clinic infrastructure, organization, space, and equipment</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.82 ± 0.95</td>
<td>0.40</td>
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<td>MI - EI</td>
<td>VI</td>
<td>3.98 ± 0.73</td>
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<td>Access to and/or interaction with physicians (clinics, rounds, surgery observation, etc)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.82 ± 0.91</td>
<td>0.26</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.77 ± 0.90</td>
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<td>Opportunity to work with a specific type of sport or activity</td>
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<td>NI - EI</td>
<td>VI</td>
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<td>0.29</td>
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<td>MI - EI</td>
<td>VI</td>
<td>4.06 ± 0.92</td>
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<td>Access to and/or interaction with other health care professionals</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.71 ± 0.90</td>
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<tr>
<td>Residency is designed or embedded within an academic environment or university setting</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.79 ± 1.26</td>
<td>0.001*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.17 ± 1.12</td>
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<tr>
<td>The format, methods, and content of the didactic curriculum that accompanies the residency</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.67 ± 0.87</td>
<td>0.37</td>
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<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.65 ± 0.96</td>
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<td>Opportunities for teaching physical therapy students or other health care professionals during the residency program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.65 ± 1.33</td>
<td>0.02*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.34 ± 0.98</td>
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<td>Program’s affiliation with a specific sports team</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.58 ± 1.13</td>
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<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.96 ± 0.81</td>
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<tr>
<td>Regional and/or national reputation of program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.56 ± 1.05</td>
<td>0.001*</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.17 ± 0.83</td>
<td></td>
</tr>
<tr>
<td>Patient caseload diagnostic diversity and/or emphasis</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.49 ± 1.18</td>
<td>0.34</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.56 ± 0.92</td>
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<tr>
<td>Perceived camaraderie or current or past residents</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.38 ± 1.09</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.46 ± 0.74</td>
<td></td>
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<td>Parameter</td>
<td>Group</td>
<td>Categorical Ranking</td>
<td>Median Category</td>
<td>Mean</td>
<td>p-value</td>
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<tr>
<td>Program’s historical passing rate for the sports specialty exam</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.35 ± 1.32</td>
<td>0.02*</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>4.00 ± 1.08</td>
<td></td>
</tr>
<tr>
<td>Opportunities for participating in research activities during the residency program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.19 ± 1.23</td>
<td>0.34</td>
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<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.17 ± 0.88</td>
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<tr>
<td>Projected daily/weekly caseload (productivity expectation)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.09 ± 1.24</td>
<td>0.17</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.35 ± 0.84</td>
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<tr>
<td>Clinic hours (daily schedule, hours of operation, hours/week of work, etc)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.05 ± 1.26</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.19 ± 0.89</td>
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<tr>
<td>Salary offered by residency program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.05 ± 1.06</td>
<td>0.12</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.35 ± 0.81</td>
<td></td>
</tr>
<tr>
<td>Benefits package available to residents (insurance, retirement plan, continuing education, vacation, sick leave, etc)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.04 ± 1.21</td>
<td>0.12</td>
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<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.38 ± 0.82</td>
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<td>Geographic location of the residency</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.04 ± 1.40</td>
<td>0.01*</td>
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<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.53 ± 0.86</td>
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<tr>
<td>Extent and availability of library and professional journal resources</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.98 ± 1.27</td>
<td>0.25</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.88 ± 1.02</td>
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<td>Residency is designed or embedded within a clinical environment in the community</td>
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<td>NI - EI</td>
<td>SI</td>
<td>2.96 ± 1.30</td>
<td>0.26</td>
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<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.96 ± 0.97</td>
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<tr>
<td>Placement in subsequent fellowship or advanced training programs</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.96 ± 1.46</td>
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<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.93 ± 1.35</td>
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<tr>
<td>Needs, desires, or preferences of spouse or significant other</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.95 ± 1.29</td>
<td>0.001*</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.30 ± 1.12</td>
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<tr>
<td>Perceived favorable training environment for women</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.93 ± 1.77</td>
<td>0.14</td>
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<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.23 ± 1.48</td>
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<td>Perceived favorable training environment for minorities</td>
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<td>SI</td>
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<td>0.11</td>
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<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.21 ± 1.48</td>
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<tr>
<td>Residency is designed in a collaborative model between an academic institution and a private clinic partner(s).</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.92 ± 1.60</td>
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<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.61 ± 1.27</td>
<td></td>
</tr>
<tr>
<td>Length of residency training program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.91 ± 1.25</td>
<td>0.24</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.28 ± 0.80</td>
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<tr>
<td>Characteristics of the area in which the residency is located (urban vs suburban vs rural, social atmosphere, recreational opportunities, etc)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.84 ± 1.21</td>
<td>0.43</td>
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<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.00 ± 0.92</td>
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<tr>
<td>Post-interview follow-up or contact by the program (perceived likelihood of acceptance)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.49 ± 1.29</td>
<td>0.04*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>3.04 ± 1.09</td>
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<tr>
<td>Cost of living in the city where the residency resides</td>
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<td>NI - EI</td>
<td>SI</td>
<td>2.40 ± 1.13</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.96 ± 0.74</td>
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<tr>
<td>Emphasis on local, state, and/or national APTA membership and involvement</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.39 ± 1.05</td>
<td>0.41</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.46 ± 0.94</td>
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<tr>
<td>Residency accepts at least two residents in each cohort</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.35 ± 1.52</td>
<td>0.46</td>
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<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.55 ± 1.39</td>
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<td>Opportunity to pursue additional degrees or certifications at the institution</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.13 ± 1.26</td>
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<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.33 ± 1.16</td>
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<tr>
<td>Parameter</td>
<td>Group</td>
<td>Categorical Ranking Importance Range</td>
<td>Median Category</td>
<td>Mean + SD</td>
<td>p-value</td>
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<td>-------------------------------------------------------</td>
<td>----------------</td>
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<tr>
<td>Tolerance and allowances regarding remediation policies</td>
<td>Residents</td>
<td>NI - EI</td>
<td>NI</td>
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<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.15 ± 0.99</td>
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<tr>
<td>Opportunity, availability, and/or allowance for supplemental moonlighting work</td>
<td>Residents</td>
<td>NI - EI</td>
<td>NI</td>
<td>1.77 ± 1.18</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>1.95 ± 1.10</td>
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<tr>
<td>Residency accepts only one resident for each cohort</td>
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<td>NI - EI</td>
<td>NI</td>
<td>1.47 ± 0.98</td>
<td>0.12</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>1.95 ± 1.14</td>
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<tr>
<td>Opportunity for part-time and/or reduced-pace program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>NI</td>
<td>1.38 ± 0.95</td>
<td>0.18</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>1.74 ± 1.13</td>
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</tr>
</tbody>
</table>

EI: Extremely important VI: Very Important SI: Somewhat Important MI: Mildly Important NI: Not Important
* p ≤ 0.05

Table 4. Importance of various methods to acquire, exchange and disseminate residency program information

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Categorical Ranking Importance Range</th>
<th>Median Category</th>
<th>Mean + SD</th>
<th>p-value</th>
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<tbody>
<tr>
<td>Interview Day</td>
<td>Residents</td>
<td>MI - EI</td>
<td>EI</td>
<td>4.45 ± 0.74</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>EI</td>
<td>4.40 ± 0.84</td>
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<tr>
<td>Email contact with program director and/or faculty</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>4.11 ± 0.99</td>
<td>0.16</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.30 ± 0.72</td>
<td></td>
</tr>
<tr>
<td>Phone contact with program director and/or faculty</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.06 ± 1.13</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.27 ± 0.79</td>
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</tr>
<tr>
<td>Program's Website</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.93 ± 1.02</td>
<td>0.27</td>
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<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.92 ± 0.77</td>
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<tr>
<td>Contact with previous/current residents</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.80 ± 1.12</td>
<td>0.04*</td>
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<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.30 ± 0.71</td>
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<tr>
<td>RFPTCAS information and links</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.61 ± 1.12</td>
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<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.71 ± 0.80</td>
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</tr>
<tr>
<td>Participation in the match day notification process</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.24 ± 1.58</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.69 ± 1.40</td>
<td></td>
</tr>
<tr>
<td>CSM TeamMates reception</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.80 ± 1.28</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.80 ± 1.13</td>
<td></td>
</tr>
<tr>
<td>Social Media (Facebook, Twitter, etc)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.50 ± 1.14</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.91 ± 1.05</td>
<td></td>
</tr>
<tr>
<td>Printed Materials or Brochures from the program</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.31 ± 1.26</td>
<td>0.04*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.64 ± 0.89</td>
<td></td>
</tr>
<tr>
<td>Online blogs, internet sites, chat rooms</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.18 ± 1.21</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.43 ± 0.89</td>
<td></td>
</tr>
</tbody>
</table>

EI: Extremely important VI: Very Important SI: Somewhat Important MI: Mildly Important NI: Not Important
* p ≤ 0.05

likelihood of post-residency employment retention as being an influential factor in decision-making (p = 0.01) (Table 5)

DISCUSSION

The results of the survey give preliminary insights into the
Table 5. Factors and criterion that are important to the match and selection of a resident to a specific residency/fellowship program.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Categorical Importance Range</th>
<th>Median Category</th>
<th>Mean</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interview performance</td>
<td>Residents</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.70 ± 0.50</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.78 ± 0.47</td>
<td>0.15</td>
</tr>
<tr>
<td>Letters of recommendation</td>
<td>Residents</td>
<td>MI - EI</td>
<td>EI</td>
<td>4.47 ± 0.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>SI - EI</td>
<td>EI</td>
<td>4.33 ± 0.75</td>
<td>0.13</td>
</tr>
<tr>
<td>Future career goals</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.28 ± 0.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.12 ± 0.86</td>
<td>0.37</td>
</tr>
<tr>
<td>Content of application essay(s)</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.21 ± 0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>4.18 ± 0.78</td>
<td></td>
</tr>
<tr>
<td>PT school clinical rotation and/or previous job performance</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.84 ± 0.77</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.80 ± 0.89</td>
<td></td>
</tr>
<tr>
<td>Previous certifications, licenses, credentials, or specific work experience</td>
<td>Residents</td>
<td>MI - EI</td>
<td>VI</td>
<td>3.67 ± 0.91</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.69 ± 0.87</td>
<td></td>
</tr>
<tr>
<td>Previous relationship with program and/or faculty</td>
<td>Residents</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.54 ± 1.00</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>VI</td>
<td>3.49 ± 1.06</td>
<td></td>
</tr>
<tr>
<td>Past research accomplishments and/or expressed interest in conducting research</td>
<td>Residents</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.33 ± 0.81</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.25 ± 0.78</td>
<td>0.26</td>
</tr>
<tr>
<td>Reputation of physical therapy school attended</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.21 ± 1.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.98 ± 0.90</td>
<td>0.06</td>
</tr>
<tr>
<td>Involvement in local, state, or national professional organizations</td>
<td>Residents</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.19 ± 0.81</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - EI</td>
<td>SI</td>
<td>3.30 ± 0.75</td>
<td></td>
</tr>
<tr>
<td>Previous continuing education experiences</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>3.07 ± 0.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - VI</td>
<td>SI</td>
<td>2.96 ± 0.79</td>
<td>0.26</td>
</tr>
<tr>
<td>Likelihood of employment retention post residency</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.98 ± 1.37</td>
<td>0.01*</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.41 ± 1.15</td>
<td></td>
</tr>
<tr>
<td>PT school class rank (GPA and/or transcript findings)</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.88 ± 1.10</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - VI</td>
<td>SI</td>
<td>2.67 ± 0.94</td>
<td></td>
</tr>
<tr>
<td>Pro bono or community service record</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.79 ± 0.94</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.82 ± 0.78</td>
<td></td>
</tr>
<tr>
<td>Geographical location preference for future employment</td>
<td>Residents</td>
<td>NI - EI</td>
<td>SI</td>
<td>2.64 ± 1.23</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.33 ± 1.11</td>
<td></td>
</tr>
<tr>
<td>Geographical background/heritage</td>
<td>Residents</td>
<td>NI - EI</td>
<td>MI</td>
<td>2.04 ± 1.21</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Faculty</td>
<td>MI - VI</td>
<td>MI</td>
<td>1.73 ± 0.82</td>
<td></td>
</tr>
</tbody>
</table>

EI: Extremely important VI: Very Important SI: Somewhat Important MI: Mildly Important NI: Not Important
* p < 0.05

Attributes, attitudes, motivations, and values of applicants to sports physical therapy residency and fellowship programs and contrast these perspectives with the perceptions of the faculty members who provide these training experiences. The survey respondents appear to be representative of the subjects of interest and their demographic characteristics are representative of the AASPT membership and other research projects of similar intent.4–8,14,15,17 It appears that applicant’s impetus to pursue residency training is intrinsically driven as they demonstrate autonomous motivations that fully endorse and show commitment to training for the sake of training. They pursue residency opportunities to access accomplished mentors who will enhance their abilities to think, reason, and appropriately apply evidence in their decision-making in a...
specific discipline in which they can establish a professional network of colleagues. The applicants appear to value personal growth, achievement, and knowledge acquisition that will benefit both their athletic patients and the profession in which they serve. They are less inspired by externally controlled rewards such as titles, recognition from other health care providers, or the capacity for improving their future salary compensation package. These factors are very consistent with the findings of Gusman et al and Osborne et al from broader surveys of physical therapy residency applicants.\textsuperscript{9,10}

Although only ranked at the "very important" level, residency/fellowship applicants rated the development of their future leadership skills, the establishment of life-long learning habits, and contributions to the evolution of sports physical therapy at a significantly higher level of importance than was perceived by program faculty. This finding offers further evidence to endorse the intrinsic behavioral nature that stimulates interest and commitment to residency or fellowship training in these post-professional learners.\textsuperscript{9,10,21}

The results of this survey offer keen insight to program directors, coordinators, and faculty as to what specific types of training opportunities are valued by applicants. While the applicants do not seem to be as concerned by the level of salary compensation they do seem to visualize residency training programs as a means to identifying and finding future job opportunities in the field. The job opportunities specific to sports physical therapy, particularly at the highest levels of competition (collegiate and professional environments), are limited and it appears that training applicants view advanced training as a means to be familiar with the landscape, access the influential decision-makers, and acquire the skills necessary to be viable in this relatively narrow field of job opportunities. This factor was the only motivation rated as "extremely important" by the applicant cohort. This finding is consistent with the finding of Briggs et al that identified that employers rate residency and fellowship-trained clinicians superior in the domains of leadership, communication, clinical aptitude, scholarship, and teaching.\textsuperscript{14} Residency faculty should be cognizant of this variable and ensure that the training circumstance they provide is consistent with the applicant’s future employment aspirations.

Other incentives that were rated significantly higher by applicants as a rationale for applying to a particular residency program centered on educational opportunities. Resident applicants highly valued a residency program housed within an academic institution with ample opportunity for supplemental learning activities and the chance to teach. It is unclear if this tendency was influenced by the nature of the survey items or if the invitations to potential applicants were biased by a larger percentage of academic education providers encouraging participation. However, this sentiment is consistent with the findings of Hartley et al in their survey of applicants from a variety of specialty disciplines in physical therapy.\textsuperscript{11}

Motivations that may have been overrated by program faculty as a rationale for application to a particular program included the perceived reputation of the program, the program’s past specialty examination pass rate, the geographic location of the program, and the needs/desires of the applicant’s significant other. The considerations for location and needs of a significant other may be mitigated by the fact that the typical residency training commitment is only for one year and many applicants and their spouses may be young enough to not yet have established familial or occupational roots in a particular community. While still rated as "very important" by applicants, residency faculty may be surprised by the comparatively lower significance assigned to program reputations and exam pass rates. The extremely high historical pass rates for all residency program graduates and high accreditation benchmarks may assure applicants that all programs have high standards and successful examination outcomes.

Analysis of the results highlighted other areas that both cohorts concur to be of higher importance in identifying desirable training opportunities. These include the recognition of a kindred connection with program faculty who possess exemplary qualifications and experience. Additionally, it appears that the applicant’s personal network of advice from respected mentors and colleagues is valued more than the general reputation of a particular program. Variables that seem to have little influence on a training site’s appeal include the availability of part-time participation, the number of other residents in the training cohort, the ability to moonlight during residency, or the future educational training opportunities at the residency institution.

To make intelligent decisions on where to apply or accept post-professional training opportunities it is necessary to acquire, exchange, and disseminate information between the training sites and the potential applicant candidates. The survey results indicate that both cohorts have similar perspectives on the most effective ways to communicate program information. Both groups valued email and phone contact with program personnel as influential in deciding where to apply and using the interview day to clarify how well the needs of both entities could be met. The face-to-face interaction, typically offered on an interview day, was rated as extremely important in helping each party decide upon the suitability of the applicant and the congruency of the desired learning opportunity. The survey did not evaluate the benefit or impact of the Mobilize platform provided by the AASPT website to help inform applicants of the unique characteristics inherent to each residency training program as it was not available at the time of the investigation. It is likely this vehicle will become a valuable repository of residency program information that will be beneficial to all sports physical therapy academy members.

The final section of the survey evaluated which factors and criteria are influential in matching residents to programs. In all but one instance, the resident and faculty cohorts agreed on the importance of each potential selection criterion. The variables that were rated by both groups as "extremely important" could be divided into factors that helped the applicant get an interview and the criterion that was used to distinguish which of those interviewed were offered residency employment. Letters of recommendation from applicant’s faculty, clinical instructors, and previous employers along with the content of their essay question responses were highly rated as a means to identify applicants that could be successful in a given program. The ap-
Applicant interview performance, previous relationships with program faculty, and personal certifications, licenses, and experience were all important in honing the application field down to those who receive an appointment offer. The one item in which residents perceived the program would rate as more important was the likelihood of the resident staying with the institution after the conclusion of their training. This finding would indicate that programs do not necessarily view residency training programs as an employee retention tool although the nature of this study design cannot be conclusive in this perspective.

Despite an array of noteworthy findings, this descriptive study is not without limitations. While the survey appears to be comprehensive in scope it is possible that influential characteristics, factors, or criteria were not evaluated. Additionally, the applicant cohort included all respondents who indicated they had applied to a residency program independent of acceptance or completion of the program. Similarly, the program cohort represented both program directors and faculty. In both cases, no attempt was made to distinguish the perspectives of the different types of survey respondents assigned to each group. Also, the survey did not identify the type of sponsoring programs (hospital-based, academic, private-practice, etc) so it is not possible to generalize these findings to a specific type of organizational structure. Additionally, the nature of the survey did not allow the respondents to request clarifications on survey questions which allows for the possibility of some items being erroneously interpreted by the respondent. While the response rate of 69% is high, it does not represent all programs and has a 5% margin of error. It is also important to note that these results only reflect the perspectives of personnel involved with sports physical therapy post-professional training. Consequently, the results of this survey should not be generalized to other specialty disciplines accredited by the ABPTRFE. As the purpose of the project was exploratory, it should be noted that Bonferroni correction for multiple comparisons were not conducted so there is a likelihood that many, if not all, of the factors may not represent significant differences between applicant and faculty cohorts.

CONCLUSION

Post-professional residency and fellowship training appears to be a relationship-focused interaction. Both faculty and applicants value direct communication and acknowledge the importance and worth of mentorship-based communications and the establishment of long term network relationships. Sports resident applicants are particularly motivated by the opportunity to make connections in a niche field of practice and perceive residency and fellowship training as means by which to enhance their employability in a competitive job market.

While the motivations for residency training may be slightly different between residency provider and recipient cohorts the importance of information acquisition and methods for residency selection criteria seem quite congruent. However, residency faculty may underestimate the importance of some of the most important motivations that prompt interest in residency training. Chief among these motivations is the intrinsic catalyst for learning. Recognition of these factors may affect how residency program content and experiences are constructed and delivered.

ACKNOWLEDGMENTS

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CONFLICTS OF INTEREST

I declare that I do not have any conflicts of interest in the authorship or publication of this contribution.

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Serial Within-Session Improvements in Ankle Dorsiflexion During Clinical Interventions Including Mobilization-With-Movement and A Novel Manipulation Intervention – A Case Series

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Keywords: ankle, manual therapy, mobilisation-with-movement, manipulation, stiffness, dorsiflexion

Background
Persisting reductions in ankle dorsiflexion range of motion are commonly encountered clinically and seen to be associated with adverse outcomes after ankle and other lower extremity injuries. Accordingly improving identified deficits is a common goal for rehabilitation; however, little data exists documenting any improvement related to interventions in these patients.

Purpose
To document the change in dorsiflexion range of motion after stretching and mobilization-with-movement and exercise and a novel manipulation intervention in a population of injured athletes.

Design
Case series in 38 consecutive injured athletes with persisting reductions in ankle dorsiflexion range of motion (42 "stiff" ankles, 34 uninjured) in an outpatient sports physiotherapy clinic.

Method
During a single treatment session, two baseline measurements of weight-bearing dorsiflexion were taken at the start of the session to establish reliability and minimum detectable change, and then the same measures were performed after stretching and a mobilization-with-movement intervention, and again after clinical exercise and a novel manipulation which was applied on both ankles.

Results
Excellent reliability was demonstrated (ICC2,1>0.93, MDC=3.5°) for the dorsiflexion measure. Statistically significant (p<0.01), but clinically meaningless improvements were seen after stretching and the mobilization-with-movement intervention on the injured and uninjured legs (1.9° and 1.4° respectively) with greater improvements seen after exercise and the subsequent manipulation (6.9° and 4.7°).

Conclusions
The relatively simple clinical exercise and manipulation intervention program was associated improvement in dorsiflexion range of motion in this cohort with persisting ankle stiffness. The interventions described largely restored range of motion consistent with baseline levels of the uninjured ankles. Improvements were also seen in the
INTRODUCTION

Despite recent international consortium and clinical practice guideline recommendations that ankle dorsiflexion range of motion be targeted during rehabilitation after ankle injury, evidence to guide the clinician regarding the effects of specific interventions remains unclear. Dorsiflexion range of motion limitation has been identified as a prospective risk factor for a number of lower-limb injuries including ankle injury, Achilles tendinopathy, patellofemoral pain, plantar fasciopathy, and hamstring injury. Additionally, limited ankle dorsiflexion range of motion is associated with impaired dynamic balance and increased chronicity and recurrence in those recovered from lateral ankle sprain. Those with chronic lateral ankle instability display lower dorsiflexion range of motion during gait as well as drop jumps, and presumed compensatory movements in other parts of the kinetic chain. During rehabilitation from ankle injury, restoration of this range of motion is often identified as an important treatment goal to address impairment.

Weight-bearing dorsiflexion range of motion is typically measured as a "knee to wall" distance, or as an angle of inclination of the tibia. Previously we have documented normal dorsiflexion range of motion as approximately 35° in an athletic population using this measure. Many physiotherapy interventions have been described to improve ankle dorsiflexion range of motion including electrotherapy, ice application, relaxation and imagery programs, passive mobilization, psychological interventions, stretching, and mobilization with movement techniques. Manual therapy interventions (joint mobilization, mobilization with movement, and high velocity low amplitude techniques) used on patients with reduced dorsiflexion after ankle injury have shown short-term improvements of 6 to 22mm and 3.0° to 5.5° depending on the intervention and measurement method employed. Stretching interventions have shown short-term improvements in range of 2° to 5.3° depending on the technique and duration with larger effects seen for two- to six-week home programs.

Research in this area typically examines single interventions in a pre- post- treatment design considering only the immediate effects of intervention. Multiple applications of joint mobilizations appear to show no further benefit beyond the second application, although this research is sparse in professional athletes. Clinically, therapists will often employ a number of interventions on any single patient during a single session. It is not known if the addition of further interventions provides greater improvement in range of motion, and it is unusual to have any published information regarding anything other than the immediate effects of such interventions. It is possible that some improvement in range of motion is simply due to either test-retest variability independent of any real gain in flexibility, or test-retest improvement. Clinically, therapists will often aim to improve range of motion and then capitalize on this by performing other exercises in this newly acquired range of motion in an effort to provide a more lasting benefit. It is not known if these gains persist throughout the duration of any clinical encounter.

Accordingly, the purpose of this case series was to document the change in dorsiflexion range of motion after stretching and mobilization-with-movement and exercise and a novel manipulation intervention in a population of injured athletes. It was hypothesized that each of the interventions would be associated with an increase in dorsiflexion range of motion.

METHODS

Patients attending an outpatient sports physiotherapy clinic were targeted for inclusion after clinical identification of a relative reduction (compared to the uninjured side) in dorsiflexion range of motion along with one of several features during rehabilitation which suggested the athlete required more ankle joint dorsiflexion to reestablish normal movement under load. These features included observation of excessive pronation on the injured side during a bilateral squat, weight-shift toward the uninjured leg during a heavy squat, off-loading of the injured leg during bilateral jump-landing, reduced distance toward the posterior targets during star excursion balance testing on the injured leg. Four broad categories of patients were examined who had a reduction of ankle dorsiflexion identified as a therapeutic limitation. The first group were athletes at end-phase rehabilitation following knee injury with painless difficulty achieving full range during full squats or unable to land properly from a jump (6 patients with 7 stiff ankles). The second through fourth groups were all pain-free patients being treated for foot (second group), ankle (third group), or posterior lower leg (fourth group) injuries with similarly interfering ankle stiffness whose rehabilitation had persisted for more than 6 weeks (32 patients with 35 "stiff" ankles, Figure 1).

Contraindications for inclusion were medical diagnosis of acute anterior or posterior impingement, imaging-identified cartilage damage, or history of cartilage repair in either the tibiotalar or subtalar joints. Additionally, any patient from either group complaining of an ankle pain during active dorsiflexion, plantarflexion, one leg squat, one leg jump, or one leg hop were excluded.

Pilot investigation suggested that an improvement of approximately 5° (0.5° SD) was possible for this intervention. Thirty-three subjects would give a power of 0.8 to detect such an effect with a Type I error rate of 0.05, therefore we planned to enroll 36 subjects (allowing for data loss). Ultimately 38 consecutive patients met the inclusion criteria in this pragmatic clinical outcome trial. The study was conducted in accordance to the STROBE guidelines for cohort studies, informed consent was sought and obtained for the use of these clinical data from the patients, and the study was approved by the local ethics committee (application number: E202009010).

INTER-RATER RELIABILITY AND BASELINE MEASUREMENT

The baseline dorsiflexion range of motion was measured be-
fore any treatment or exercise was given at the beginning of the session. The patient started in a lunging position facing a wall, "knee over middle toe" where the pelvis remains parallel to the wall (Figure 1). An initial familiarization of two lunges to the limit of dorsiflexion were performed. Subjects were instructed and manually guided, if required, to maintain neutral tibial rotation during these lunges. Two physiotherapists who were blinded to the intervention, injured side(s), and to each other’s measurements recorded the subsequent clinical measurement on each ankle. For the measurement, an inclinometer (Magnetic Polycast Protractor, Empire, USA) was placed 4 fingers width proximal to the ankle joint line on the tibia avoiding the antero-lateral muscular compartment (Figure 2). Two baseline measurements were taken to determine within session inter-rater reliability, with the subject walking approximately 200m between these tests on an indoor track (Figure 2). Inter-rater reliability was assessed using ICC (2,1) (absolute agreement) and the minimum detectable change (MDC) through calculation of the Standard Error of the Measurement from the ICC ANOVA table. Statistical analyses were performed using SPSS (v23, IBM Amarok, USA) and R with the dabest 0.2.2 package.

**INTERVENTIONS**

After a self-paced warm-up on a stationary bike for approximately 10 minutes, the patient had a series of three, 10-second mobilization with movement techniques performed on each ankle (Figure 3) at a rate of 1Hz followed by soleus and gastrocnemius self-stretching for 3 repetitions of 30 seconds each with 10 seconds rest between repetitions (Figure 4). Immediately after this, dorsiflexion measurement was taken by the experimental physiotherapist, blinded to the baseline measurements. The only difference in measurement technique described above is that no familiarization trials were conducted. The patient then continued with their scheduled rehabilitation treatment session. Typically, this session would include a variety of balance, strength, and coordination exercises relevant to the athlete’s sport and their rehabilitation stage. After one hour of rest that followed the end of this session, the athlete was then recalled for a manipulative intervention technique which was applied to both ankles. After this intervention, the dorsiflexion range of motion was again assessed by an independent physiotherapist, blinded to the previous findings in a similar manner to the previous measurements (with no warm-up trials).
MOBILIZATION WITH MOVEMENT

The technique utilized incorporated Mulligan principles of applying subtle pain-free overpressure to an end-range movement, or specifically a "sustained passive accessory force / glide to a joint while the patient actively performs a task that was previously identified as being problematic." The patient was supine, foot off the edge of the treatment plinth so that the joint line is about 1 cm away from its edge (Figure 3). A rigid mobilization strap was placed at the level of the joint line its length is then adjusted to be 5 cm from the floor. The belt was folded at its upper part to cover the anterior surface of the talus only (i.e., avoiding coverage of the other tarsals and/or the tibia). The clinician inserted his foot in its lower part to create a downward pressure on the talus. While controlling the stability of the tibia with one hand ensuring full knee extension along the maneuver, the other hand grasping the heel and passively mobilizing the foot from plantarflexion to dorsiflexion. Three sets of 10 consecutive mobilizations with movement are applied with 10 seconds rest between sets.

STRETCHING

Soleus and gastrocnemius stretching were performed standing on a small (6.5 cm) platform for 3 repetitions of 30-seconds each with 10 seconds rest after each stretch (Figure 4).

MANIPULATIVE TECHNIQUE INTERVENTION

The manipulation technique (Figure 5) was performed on both ankles without any additional warm-up.

RESULTS

SUBJECT CHARACTERISTICS

Subject characteristics are presented in Table 1. One subject was unable to be measured for the final (post-manipulation) measurement. Sensitivity analysis (imputing these missing data from linear regression) showed no meaningful differences therefore these data were omitted from the final analysis.

RELIABILITY AND MINIMUM DETECTABLE CHANGE

Given the differences in range of motion for the uninjured and injured legs, inter-rater reliability was calculated initially for the injured (ICC2,1 (absolute error) = 0.96, 95% confidence interval: 0.93 to 0.98, p<0.01) and uninjured (0.98, 0.98 to 0.99, p<0.01) legs separately, and then for all legs combined (0.98, 0.97 to 0.99, p<0.01). As these results were essentially the same the pooled (all legs) results are used for calculation of the minimum detectable change which was 3.5°. These measurements and the between group differences are depicted using bootstrap confidence intervals in Figure 6.

TREATMENT EFFECTS

A one-way repeated measures ANOVA was conducted to see if there were statistically significant differences in dorsi-

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flexion range of motion at the three time points (Baseline measurement 1, post-MWM, and post-manipulation) for each of the injured and uninjured legs separately. There were no outliers and the data were normally distributed (visual inspection, Q-Q plots, and Shapiro-Wilk tests). The assumption of sphericity was met for both analyses (injured legs: $\chi^2 = 8.59, p = 0.014$; uninjured legs: $\chi^2 = 9.97, p = 0.007$). After post-hoc adjustment for multiple comparisons (Sidak) statistically significant differences were seen for dorsiflexion at all time points ($p<0.01$) except for the two baseline measures. It should be noted however that only the differences between baseline and manipulation for the injured and uninjured legs (6.9° and 4.7° improvement respectively), and injured leg mobilization with movement to manipulation (5.1°) exceeded the dorsiflexion minimum detectable change of 3.5°. These differences are depicted using bootstrap confidence intervals in Figure 7 and Table 2.

Between group comparisons for the baseline (reliability) measures, and the first baseline measure compared to the post-mobilization with movement, and post-manipulation conditions for both the injured and uninjured legs. Note that the MDC for this measure is 3.5° therefore the only measurements to be considered clinically significant are: the injured leg from baseline to post-Manipulation and from post-MWM to post manipulation, while for the uninjured leg only baseline to post-manipulation reached this hurdle ("MWM": mobilization with movement).

DISCUSSION

The approach described here documents, for the first time, baseline dorsiflexion range of motion, and test-retest reliability for this measure along with in-session measurements after both a mobilization-with-movement and stretching, and exercise and a novel manipulation intervention. The stretching and mobilization with movement was associated with a likely clinically insignificant improvement of approximately 1-2°, and a further improvement of about 4-5° after the exercise treatment and the novel manipulation technique. The combination intervention appears to largely restore the injured ankle dorsiflexion range of motion compared to the baseline range of the healthy ankle (from 28° to 35° and 37° respectively). Previously we had documented healthy athletes’ weight-bearing dorsiflexion range of motion to be approximately 35° which suggests this combination of interventions is restoring "normal" range of motion in athletes. It should be noted however that the uninjured ankle demonstrated an improvement of a similar magnitude compared to the injured ankle. It is not clear if the therapeutic target value of the baseline uninjured ankle’s range of motion is appropriate, or if clinicians should aim for the “best possible” range available on the uninjured ankle.

The effects of the clinical intervention demonstrated here reflect usual clinical (multimodal) practice. Typically, clinical research will consider only a single intervention performed in isolation which allows for a clearer depiction of such an isolated intervention. This does not reflect usual clinical practice however where multimodal interventions are commonplace during an encounter. The authors’ suggest that this approach may be useful to further tease out aspects of a clinical encounter which contribute to improvements as well as their relative contributions, although future research will need to consider the order of application, more frequent measurements, the longer-term maintenance of these ranges of motion, and whether these improvements in flexibility transfer to daily activities.

The actual anatomic effects of the interventions cannot...
be inferred from this research. While some researchers ascribe treatment benefits to changing joint mechanics others suggest combinations of soft tissue relaxation and/or stretch tolerance are more important factors. The data presented here suggests that stretch tolerance is less likely to be a major contributor to the improvements seen given the two baseline measures remained essentially unchanged however beyond this we are unable to speculate as to exactly how these ranges of motion are improving. Future work might consider muscle tone, tissue compliance, and arthrokinematics as potential sources of the improvements seen.

To the authors’ knowledge, there is little research describing within-session changes in populations of ankle injured athletes with reduced dorsiflexion undertaking typical multimodal rehabilitation. Serial changes after repeated application of the same (mobilization) intervention or the results of complete heterogenous treatment approaches are more commonly reported. These approaches do not allow understanding of the different components of usual multimodal interventions and require different research methods.

Importantly, the changes seen here are only documented within the session, in a static measurement, not during gait or other athletic tasks. Future research should examine the time course of these changes, specifically how long changes persist in the absence of further intervention, and whether these static improvements in flexibility are associated with altered kinematics and kinetics during functional tasks such as running, jumping, and direction change. These limitations notwithstanding, the previously documented association of reductions in dorsiflexion range of motion with adverse outcomes make the current findings likely of interest to clinicians and researchers alike.

CLINICAL IMPLICATIONS

The multi-modal intervention presented here resulted in potentially clinically important improvements in ankle dorsiflexion range of motion in a population that had failed to show sufficient improvement in this rehabilitation goal. Incremental improvements were seen with both the mobilization with movement and stretching, and subsequent exercise and manipulation interventions. Clinically, the authors have noticed this combination of treatment interventions to show larger effects than any single intervention in the management of ankle dorsiflexion range of motion deficit. While we might attribute short-term improvements in flexibility to the application of manual therapy techniques, clinicians should consider the possibility that the exercise interventions may have contributed to these improvements when applied in combination with these techniques. The order of applications as well as the dose and the grade of the manual therapy techniques (repetitions and force applied) and exercises should be investigated in future research.

LIMITATIONS

Due to the nature of the clinical setting, this research was conducted only on adult male professional athletes; extrapolation to adolescents, females, and non-athletes should be done with care. As we only measured dorsiflexion range of motion four times during each session, we are unable to describe the independent effects of the exercise and manipulation interventions performed, nor the possible effects of a sham intervention. Future research could address this limitation but would need to control for differences in exercise prescription and baseline characteristics of the patients. The longer-term effects of these interventions were not documented need to be investigated in future research.

CONCLUSION

A combination of a mobilization with movement, exercise and stretching, and a novel manipulation induced changes in weight-bearing ankle dorsiflexion which were likely clinically meaningful. These represent relatively simple interventions which can be safely applied clinically for patients with persisting restrictions in ankle dorsiflexion. Future research needs to describe how long these changes are maintained, and if these changes are associated with other functional improvements such as performance and re-injury risk.

CONFLICTS OF INTEREST

The authors state no conflict of interest perceived or actual in the creation of this research.

Table 1. Summary subject characteristics

<table>
<thead>
<tr>
<th>Age</th>
<th>Height</th>
<th>Weight</th>
<th>BMI</th>
<th>Professional sport (n)</th>
<th>Recreational sport (n)</th>
</tr>
</thead>
</table>
| Mean: 29.1 (SD: 6.4, Range: 18 to 54) | 179.3 (SD: 8.7, Range: 161 to 202) | 79.4 (SD: 15.6, Range: 58 to 127) | 24.6 (SD: 4.0, Range: 19 to 37) | Football: 25 | Ice hockey: 1
| Basketball: 3 | Volleyball: 3 | Rugby: 3 | Handball: 2 | Track & field: 1 |

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Table 2. Between group comparisons for the baseline (reliability) measures, and the first baseline measure compared to the post-mobilization with movement, and post-manipulation conditions for both the injured and uninjured legs

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference (95% confidence interval)</th>
<th>t</th>
<th>df</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injured Baseline 2 – Injured Baseline 1</td>
<td>0.18° (-0.34° to 0.71°)</td>
<td>0.70</td>
<td>41</td>
<td>0.49</td>
</tr>
<tr>
<td>Uninjured Baseline 2 – Uninjured Baseline 1</td>
<td>-0.09° (-0.52° to 0.35°)</td>
<td>-0.40</td>
<td>33</td>
<td>0.69</td>
</tr>
<tr>
<td>Injured Post-MWM – Injured Baseline 1</td>
<td>1.92° (1.30° to 2.53°)</td>
<td>6.28</td>
<td>41</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Uninjured Post-MWM – Uninjured Baseline 1</td>
<td>1.36° (0.72° to 2.01°)</td>
<td>4.30</td>
<td>33</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Injured Post-Manipulation – Injured Baseline 1</td>
<td>6.89° (6.09° to 7.69°)</td>
<td>17.42</td>
<td>40</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Uninjured Post-Manipulation – Uninjured Baseline 1</td>
<td>4.74° (3.71° to 5.78°)</td>
<td>9.34</td>
<td>32</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Injured Post-Manipulation – Injured Post-MWM</td>
<td>5.10° (4.50° to 5.69°)</td>
<td>17.29</td>
<td>40</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Uninjured Post-Manipulation – Uninjured Post-MWM</td>
<td>3.49° (2.60° to 4.38°)</td>
<td>8.01</td>
<td>32</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Note that the MDC for this measurement is 3.5° therefore the only measurements to be considered clinically significant are: the injured leg from baseline to post-Manipulation and from post-MWM to post manipulation, while for the uninjured leg only baseline to post-manipulation reached this hurdle (“MWM”: mobilization with movement).

Figure 6. Baseline dorsiflexion measures for both the injured and uninjured groups along with bootstrap estimated paired mean differences.

The two slopegraphs on the left are the two measures each for the uninjured and injured legs. To the right is the bootstrap estimated group mean difference for the injured and uninjured legs along with its distribution.
Figure 7. Estimation plot of dorsiflexion range of motion at: baseline (first measurement), post-stretching and mobilization-with-movement, and post-clinical exercise and then manipulation (upper panel - injured ankles filled circles on the left, uninjured on the right). Lower panel shows the bootstrap estimated mean differences for both the injured and uninjured legs (with the associated 95% confidence intervals) along with standard and confidence interval for these estimates.

Dashed horizontal line in the mean difference panel is placed at 3.5° representing the MDC for the dorsiflexion measure.

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REFERENCES


Serial Within-Session Improvements in Ankle Dorsiflexion During Clinical Interventions Including...


ACL Return to Sport Testing: It’s Time to Step up Our Game

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Physical Therapy, Robbins College of Health and Human Sciences, Baylor University, Health Sciences, Rocky Mountain University of Health Professions, Wise Physical Therapy and Sports Medicine

Keywords: acl, return to sport, hop testing, return to sport testing, movement system, knee

Patients and physicians have long looked to physical therapists to help determine an athlete’s readiness to return to sport (RTS) following anterior cruciate ligament reconstruction (ACLR). This is a complex decision that must take into account biological healing, joint stability, functional performance, and psychological readiness. Considering that the vast majority of medical professionals use time as the sole determinant of an athlete’s readiness, and few are using performance-based criteria, it appears as though our profession is failing to capture the necessary information to make this weighty recommendation. The time is now to take a hard look at current practice patterns with RTS testing and push the envelope forward. The purpose of this clinical commentary is challenge our failing status quo by disseminating a robust model for RTS testing that incorporates temporal and criterion-based factors, as well as intrinsic and extrinsic data.

Level of Evidence

5

REVIEWING CURRENT PRACTICE PATTERNS

Anterior cruciate ligament (ACL) injuries are all too common in athletic participation. Sources have reported the incidence as high as 200,000 ACL injuries per year in the United States alone. It is customary in the United States to pursue anterior cruciate ligament reconstruction (ACLR) after injury in order to return to the previous level of sport. While many healthcare professionals and athletes are painfully aware of how common ACL injuries are, few realize, or at least openly acknowledge, that the likelihood of returning to sport is far from guaranteed. Pooled data from a systematic review and meta-analysis found that only 65% of individuals returned to their preinjury level of sports participation following an ACLR, with only 55% going on to participate in competitive sports. Other studies have shown that, of those athletes under 25 years of age, approximately 25-29% will go on to incur a second ACL injury. While there are many factors to consider when reviewing this data, it should, at minimum, cause us all to question whether the current state of ACL management is acceptable. Stakeholders would benefit from taking a step back and reflecting on whether current practice patterns reflect what is truly in an athlete’s best interest.

Sports medicine personnel should acknowledge and respond to the problem of high reinjury rates and relatively low rates of returning to sport. A recent scoping review identified the most common criteria used to clear individuals to RTS after primary ACLR. Of the 209 studies reviewed, 85% reported the use of time as a criterion for RTS, with 42% using it as the sole criterion. This fixation on using time as a RTS determinant is deeply engrained in the physical therapy profession, so much so that ever since Dr. Shelbourne began discussing accelerated rehabilitation after ACLR in the 1990’s, patients and sports medicine providers have pushed the speed limits of rehab. Kevin Wilk spoke to this in 2005, poignant noting, “Speeding through the rehabilitation program may have more risks than benefits. When we speed in our automobiles we may be caught by the law and pay a fine. If we speed in the rehabilitation program, we may have to suffer more significant consequences—patients with unsatisfactory knee function for the rest of their lives.” The authors of this manuscript argue that the majority of sports medicine professionals — physicians and physical therapists alike – are dangerously exceeding the speed limits of rehab.

Looking closer at the issue of time as a RTS determinant, Burgi et al. noted that 72% of practitioners use ≥6 to <9
months as their standard to clear an athlete for play. Is waiting six to nine months sufficient to maximize potential for a safe RTS? The vast majority of the time, the answer is an emphatic, NO! Cristiani et al. found that of 4095 individuals assessed at six-months post-operative ACLR, only 35% and 47% achieved ≥90% limb symmetry for isokinetic quadriceps and hamstring strength, respectively. Additionally, only 67% achieved ≥90% limb symmetry for a single-leg hop test. Collectively, only 19.6% achieved symmetrical knee function with all three standardized tests (isokinetic quadriceps strength, isokinetic hamstring strength, and single-leg hop test). Similar data has been shown for athletes nine months post-operatively, noting that only 11% of subjects (7 of 62) passed RTS testing that included the Landing Error Scoring System, three single-leg hop tasks, isokinetic quadriceps and hamstring strength, as well as two outcome measures (IKDC and ACL-RSI). A similar study had equally striking findings, noting a seven-fold greater risk of injury for individuals who RTS before nine months post-operatively.

Some authors have gone so far to suggest that RTS should be delayed until two years after ACLR, noting that baseline joint health and function are not typically achieved until 24 months post-operatively; thus, delaying RTS until this is achieved significantly reduces the incidence of second ACL tears. While this may scream in the face of current practice patterns, the sports medicine community should not be quick to discount it.

The use of a limb symmetry index (LSI) is of particular interest when qualifying someone's RTS readiness. It is vital to appreciate that symmetry may not correlate with movement quality nor does it indicate whether the athlete has achieved pre-injury status or acceptable population norms. Gokeler et al. notes, "An athlete may have perfect limb symmetry and yet be under-prepared to compete because both extremities are much weaker or more poorly controlled than a healthy athlete." Despite these shortcomings, LSI is often used in association with strength and hop testing. While there is considerable variation between studies regarding an acceptable LSI, the majority of authors suggest that a LSI of 85-90% is satisfactory. While this may be normative practice, is it truly best practice? Gokeler et al. goes on to note that, "Despite achieving a LSI > 90%, patients demonstrated significant and clinical relevant deficits in performance for both limbs when compared to normative data from healthy athletes." A similar study, albeit small, demonstrated that individuals achieving a LSI of >93% still exhibited markedly asymmetrical movement patterns during hop testing. A larger study revealed that athletes who achieved >90% LSI for strength and hop testing did not achieve 90% of their estimated pre-injury capacity with the same tests. At best, all of these athletes likely demonstrate compensatory adaptations (eg. detraining) on their uninjured extremity; at worst, they demonstrate involuntary neurologic inhibition of the uninjured limb due to the contralateral ACL tear.

No matter the mechanism, one can conclude that using LSI for hop testing and strength assessment has the potential to overestimate knee function. Therefore, interpretation of this data must be done cautiously. To be clear, the authors of this manuscript are not suggesting practitioners abandon LSI altogether; instead, the authors advocate for careful interpretation of the data in addition to raising the bar for what is considered passing. Clinical practice guidelines recommend a minimum of 90% LSI, yet advocate for a much higher standard of up to 100% symmetry. It is the opinion of the authors that despite the limitations associated with using LSI for RTS testing, and the apparent lack of consensus regarding passing scores, athletes should aim for 100% LSI for both strength and hop testing, with 97% the lower cutoff for hop testing and 90% the lower cutoff for isokinetic strength testing.

Another area that should draw attention in current practice is the use of patient-reported criteria. For example, in Burgi’s scoping review, only 12% of studies assessed personal or contextual factors, including confidence and self-reported knee function. The low utilization of patient-reported assessments contrasts recommendations from recent literature demonstrating that lower psychological readiness correlates with a higher risk of second ACL injury when returning to play among younger patients. Lower psychological readiness can also lessen the likelihood that an individual returns to sport at all, inciting fear of reinjury and decreased self-efficacy, even after one is deemed physically ready to return to play.

As readers evaluate current practice patterns for ACL injury management, it is important to compare how these stand up to current recommendations. A consensus statement on RTS from the First Congress in Sports Physical Therapy outlines five specific recommendations to guide the practitioner when deciding to clear an individual for RTS.

1. Use a group of tests (aka: a test battery).
2. Choose open tasks (less controlled) over closed tasks (more controlled) when possible.
3. Include tests with reactive decision-making elements.
4. Assess psychological readiness to RTS.
5. Monitor workload throughout the RTS transition.

When examining these recommendations in light of current practice patterns, it is clear that a sizeable gap exists. In retrospect, it appears as though the sports medicine community may have a monocular, often short-sighted view of ACL rehabilitation and RTS testing, which may be a notable contributor to low RTS rates as well as high reinjury rates. In response to this hypothesis, the authors of this manuscript aim to disseminate a robust model for RTS testing that incorporates temporal and criterion-based factors, as well as intrinsic and extrinsic data.

**LET’S GET BACK TO THE BASICS**

It is commonplace for sports physical therapists to commence an athlete's rehabilitation by creating a needs analysis that details his or her athletic demands. Take for instance, a high school soccer player. The athlete needs to be able to sprint, cut, jump, hop, take contact from other players, give contact to other players, rapidly accelerate, and rapidly decelerate, all while filtering the onslaught of visual, proprioceptive, vestibular and somatosensory inputs. In short, the athletic demands of soccer (or any sport at that), are complex and not easily captured by one or two
Table 1. Extrinsic Criterion Used to Assess Return to Sport Readiness*

<table>
<thead>
<tr>
<th>Extrinsic Criterion</th>
<th>Means of Measuring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of motion</td>
<td>Hip, knee &amp; ankle (tibial shaft angle)</td>
</tr>
<tr>
<td>Neuromuscular control</td>
<td>Functional Movement Screen, Y-Balance Test, Single leg squat, Tuck Jump Assessment, Landing Error Scoring System</td>
</tr>
<tr>
<td>Strength</td>
<td>Isokinetic testing: time to peak torque, peak torque</td>
</tr>
<tr>
<td>Power</td>
<td>Hop testing: Anterior hop, triple hop, triple crossover hop, timed hop, hop &amp; stop</td>
</tr>
<tr>
<td>Agility and cutting</td>
<td>Trazer lateral agility screen, Trazer Flanker test, reactive agility test</td>
</tr>
<tr>
<td>Psychologic readiness</td>
<td>ACL-Return to Sport After Injury, 2000 IKDC Questionnaire**</td>
</tr>
</tbody>
</table>

*Means of measuring should be left to the discretion of the evaluating facility.

**IKDC: International Knee Documentation Committee

simple tests. Therefore, using the individualized needs analysis, specific targeted interventions and functional testing can be developed in preparation for the athlete to RTS.

While every sport is unique and criteria must be tailored for individual needs, many commonalities span athletes of all levels, positions, and sports. Table 1 offers the reader a list of extrinsic criteria that most athletes will require to minimize the potential for re-injury, along with the various means of measuring the variable. While the proposed list is not exhaustive, it offers a practical testing battery when completing RTS testing based on available literature. Table 2 provides the rationale for the proposed recommended cut-off values.

The vast majority of applied research to date has focused on modifiable risk-factors as criteria for RTS testing. There is an equally important arm of this discussion that needs to be explored: that of intrinsic risk factors. It is the opinion of the authors that many healthcare professionals often undervalue the influence of intrinsic risk factors on ACL reinjury when making RTS decisions. Female athletes, for example, are two to eight times more likely to sustain an ACL injury. Multiple anatomic factors, unable to be ameliorated by the patient, may predispose one to ACL injury. A list of these intrinsic risk factors is available in Table 3.

While these factors may indeed be non-modifiable, their correlation with ACL tears should be acknowledged and influence one's timeline for sports participation.

Practically speaking, the reader should compare two athletes who pass RTS testing seven-months following ACLR. Consider one patient who has no intrinsic risk factors: the athlete is male, a senior in college, and sustained a contact-related ACL tear during intramural flag football. In contrast, a 16-year-old female is also looking to go back to sport seven-months following ACLR. She has a history of a contralateral ACL tear, a family history of ACL tears, marked laxity of the knee, as well as a primary injury that was non-contact. Even if both athletes pass their respective RTS tests, the clinician should appreciate how uniquely different each athlete is, and how they should be managed as such. The authors offer specific recommendations for reconciling common intrinsic factors by delaying an athlete’s RTS and requiring them to complete a standardized ACL injury prevention program (IPP) that has been demonstrated to decrease the risk of ACL injury.

Figure 1. Isokinetic testing following ACLR

RTS and requiring them to complete a standardized ACL injury prevention program (IPP) that has been demonstrated to decrease the risk of ACL injury (Appendix 1).

SPECIFIC TESTING CONSIDERATION

In order to account for the plethora of modifiable and non-modifiable risk factors associated with an ACL tear, the authors propose the use of a RTS testing battery similar to Appendix 1. Make note of the "Ticket to Entry." These tests were selected as part of a screening tool in order to ensure the athlete is safe to undergo and complete RTS testing. If the athlete does not successfully pass the “Ticket to Entry,” they should not complete the remainder of the assessment.

Given the complexity of some of the tests, as well as the necessary equipment (Figures 1-3), not all outpatient phys-
Table 2. Extrinsic Cut-Off Values Used to Assess Return to Sport Readiness*

<table>
<thead>
<tr>
<th>Extrinsic Criterion</th>
<th>Source for Cuff-Off Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip, knee &amp; ankle ROM</td>
<td>While the authors of the manuscript are unaware of knee ROM loss leading to a secondary ACL tear, research suggests that a loss of knee ROM is correlated with early knee osteoarthritis. 17 Several studies have examined the link between a lack of closed chain dorsiflexion and increased ground reaction forces, altered knee kinematics, and increased risk of lower extremity injury. 18-20</td>
</tr>
<tr>
<td>Functional Movement Screen (FMS)</td>
<td>The authors use a subscription-based injury prediction algorithm titled Move2Perform in order to interpret Functional Movement Screen scores. In the absence of this, a cut score of &lt; 14 with no side-to-side discrepancies has been proposed. 21</td>
</tr>
<tr>
<td>Y-Balance Test (YBT)</td>
<td>The authors use a subscription-based injury prediction algorithm titled Move2Perform in order to interpret Y-Balance Test scores. In the absence of this, a cut score of ≤4cm difference anteriorly and ≤6cm posterolateral and posteromedial can be used. 22</td>
</tr>
<tr>
<td>Single Leg Squat Test (SLST)</td>
<td>The Single Leg Squat Test has been shown to be a simple, useful test when identifying neuromuscular risk factors for an ACL tear. 23</td>
</tr>
<tr>
<td>Tuck Jump Assessment (TJA)</td>
<td>While a cut score of ≤5 was originally proposed, this was based off of unpublished research. 24 The authors propose elevating the standard of this test to ≤3 errors when used as part of RTS testing.</td>
</tr>
<tr>
<td>Landing Error Scoring System</td>
<td>Based off Welling et al.8 and Padua et al. 25</td>
</tr>
<tr>
<td>Isokinetic testing</td>
<td>Based off Welling et al.8 and Tourville et al. 26</td>
</tr>
<tr>
<td>Hop testing (anterior hop, triple hop, crossover hop, timed hop)</td>
<td>Based off original hop test 27 and more current revelations regarding limitations of hop testing and LSI. 10-12</td>
</tr>
<tr>
<td>Hop &amp; Stop Test</td>
<td>Based off Juris et al.28</td>
</tr>
<tr>
<td>Lateral Agility Screen</td>
<td>Using a Trazer movement analysis system, lateral agility is used to assess reaction time, acceleration, and deceleration speeds of the involved and uninjured extremities. ≥95% LSI was chosen based off unpublished research and to remain fairly consistent with other cut-off scores.</td>
</tr>
<tr>
<td>Flanker Test</td>
<td>Using a Trazer movement analysis system, the Flanker test 29 was used to assess reaction time, acceleration, and deceleration speeds of the involved and uninjured extremities. ≥95% LSI was chosen based off unpublished research and to remain consistent with other cut-off scores.</td>
</tr>
<tr>
<td>Reactive Agility Test</td>
<td>Laser timing is used to assess the speed an athlete can change direction on both the involved and uninjured lower extremity. Additionally, a scoring rubric is used to assess lower quarter biomechanics during the full-speed cutting maneuver.</td>
</tr>
<tr>
<td>ACL Return to Sport After Injury (ACL-RSI)</td>
<td>Based on O’Connor et al.30 and Meierbachtol et al.15</td>
</tr>
<tr>
<td>2000 IKDC Evaluation</td>
<td>Based on Cheecharern31 and Sadeqi et al. 32</td>
</tr>
</tbody>
</table>

*Means of measuring should be left to the discretion of the evaluating facility

Physical therapy facilities are poised to conduct RTS testing. Athletes may need to be sent to specific RTS testing centers that have the equipment and expertise in order make the determination. Finally, given the implicit bias that many physical therapists have towards their own patients, and the reality that physical therapists are not only assessing the athlete during testing but, in essence, their own performance as therapists, the authors recommend having a practitioner complete the testing who was not otherwise directly involved in the patient’s care.

Lastly, while a thorough discussion on acute:chronic workload ratios is beyond the scope of this paper, the authors of the manuscript would be remiss to not mention the importance of the concept, especially in light of the current RTS Consensus Statement. 16 Simply put, as an athlete transitions back to participation, sport, and performance, it is important to achieve and maintain optimal loading. Monitoring an athlete’s current training load (acute) against the load imposed over the preceding four weeks (chronic) pro-

Figure 2. Reactive agility testing using laser timing gates
Great debate exists on and off the field regarding the utility of the acute:chronic workload ratio and its ability to predict injury. The authors refer readers to a recent systematic review detailing many of the advantages of workload monitoring, along with many of the associated controversies.

AN UPHILL BATTLE

Utilizing temporal and criterion-based assessments when making RTS decisions, as well as considering intrinsic and extrinsic risk factors, goes against the grain. It is likely that many physicians, physical therapists, and patients may look unfavorably upon these recommendations. Additionally, the proposed RTS criteria have not yet been validated. While this approach to RTS testing may provide more information than current RTS criteria, it may also be less feasible for some clinicians and patients, considering the additional equipment, training, and time required to execute it. However, the pressures for an athlete to RTS the season following their injury should not permit clinicians to put on blinders and throw clinical reasoning out the window. Instead of focusing on getting an athlete back on the field as soon as possible, what if physical therapists were to actively shift the sports medicine culture to focus on long-term athlete health and wellness, as well as athletic viability and performance? What if therapists start seeing post-operative protocols as guides and not rules, cease conveniently simplifying RTS testing to one-dimensional methods that check a box, and instead embrace a holistic approach to evaluating an athlete’s readiness for sport? What if sports medicine providers are transparent enough to arm patients with accurate RTS and retear rates instead of pretending that waiting six to nine months to RTS guarantees success? The authors of this manuscript encourage each clinician to honestly reflect on their current practice patterns for RTS testing. The time is now to push the envelope forward. Please consider joining the movement.

CONFLICTS OF INTEREST

The authors affirm that we have no financial affiliation (including research funding) or involvement with any commercial organization that has a direct financial interest in any matter included in this manuscript.

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Table 3. Intrinsic Risk Factors Associated with ACL Re-Injury

<table>
<thead>
<tr>
<th>Intrinsic Criterion</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Female</td>
</tr>
<tr>
<td>Anterior knee laxity</td>
<td>&gt;3mm translation</td>
</tr>
<tr>
<td>Mechanism of injury</td>
<td>Non-contact injury</td>
</tr>
<tr>
<td>Family history of ACL tear</td>
<td>Immediate family member with history of ACL tear</td>
</tr>
<tr>
<td>Sport participation</td>
<td>Returning to Level I sport (includes jumping, hard pivoting, cutting)</td>
</tr>
<tr>
<td>Tibial slope angle</td>
<td>Steeper posterior-inferior-directed tibial plateau slope compared to uninjured athletes, as determined by surgeon</td>
</tr>
<tr>
<td>Intercondylar femoral notch size</td>
<td>Decreased notch width index compared to uninjured athletes, as determined by surgeon</td>
</tr>
<tr>
<td>Previous ACL tear</td>
<td>History of either ipsilateral and/or contralateral ACL tear</td>
</tr>
</tbody>
</table>

provides what is known as the acute:chronic workload ratio.16
REFERENCES


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Appendix 1
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3. As compared to the depth of penetration from manual therapy vs. extracorporeal shockwave therapy, average session of time extracorporeal shockwave therapy being five minutes; decrease in muscle strain from operating an extracorporeal shockwave device compared to manual therapy on a clinician’s hands.
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